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OXIDANT CLIMATOLOGY OF ONTARIO

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CANADIAN CLIMATE CENTRE

Application and Impact Division

Report on

OXIDANT CLIMATOLOGY OF ONTARIO

by

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ATMOSPHERIC ENVIRONMENT

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OXIDANT CLIMATOLOGY OF ONTARIO

A. INTRODUCTION

Recent toxicological studies indicate good reason for concern about exposure to high concentrations of ozone, which is approximately 90% of the measured atmospheric photochemical oxidants. There is evidence that significant losses to agricultural and forest productivity are occurring in some regions of Canada. Ozone injuries to plants result from major physiological disturbances and biochemical changes within the plant system. These may be expressed as various types of leaf damage, arrested development, decreased growth and yield, destruction of flowers, and other changes that may affect the reproductive and/or genetic systems of plants. In southwestern Ontario extensive visible and invisible injuries to white beans, tobacco, vines, onions, tomatoes, cucumber, celery and forests have been reported. Ozone is also known to be hazardous to health and to damage or decrease serviceability of many materials. The main health effects are on the respiratory tract. Evidence also suggest that "ozone causes a reflex broncho-constriction initiated by stimulation of lung irritant receptors. The resulting increased airway resistance, along with decreased compliance, cause altered pulmonary function and decreased efficiency of breathing". (Preliminary report of the Canadian Federal-Provincial Committee on Air Pollution). The sub-committee on maximum tolerable levels recommended a dosage of 200 ppb for one hour. However, over the four years 1977 to 1980 only one monitoring station in Ontario, namely Windsor, recorded an hourly concentration of 211 ppb, although Anlauf et al (1975) reported ozone concentrations higher than 200 ppb on several hours in August 1975 at Toronto Island.

Studies of ozone in Canada have generally been initiated to deal with specific problems on a local and regional scale, such as the impact of ozone on vegetation, conditions promoting episodes of photochemical air pollution, and statistical analysis of measured ozone concentrations over urban and rural areas. Lately there has been increasing awareness of the ozone problem, and moves are being initiated for more organized and systematic research on all aspects of this problem, including long-range transport and impact. This report is part of these studies and deals with oxidant climatology of Ontario with the following objectives:

- (a) to compile a statistical summary of spatial and temporal ozone concentrations and persistence of episodes and associated meteorological parameters;
- (b) to characterize the various synoptic weather conditions of ozone episodes;
- (c) to determine the sources of local and long-range transported ozone;
- (d) to delineate the geographical areas potentially subject to ozone episodes.

B. DATA AVAILABILITY

Ozone was monitored by chemiluminescent instruments at a number of urban and rural locations in southern Ontario. Ozone data collected by the Ontario Ministry of the Environment for the years 1977 to 1980 inclusive were used, and the sixteen observing stations in Figure (1) were selected for this study. While it is realized that no really valid statistical conclusions can be drawn from only four years' data, it is, nevertheless, possible to characterize the various weather conditions associated with elevated ozone, except in the case of stratospheric ozone, for which there is little or no data available. Concord Scientific Corporation of Toronto prepared most of the ozone tabulations under contract to the Atmospheric Environment Service. Table (1) shows that the percentage of valid data for the four-year period was above 90% at 12 of the 16 stations. Of the remainder, Petrolia, Huron Park, Orono and Merlin had 86%, 85%, 84% and 75% respectively. Percentages for individual years were still mostly above 90%, with the exception of Orono, with 44% in 1980, and Merlin, with 48% in 1977. In 1978 a few monitoring stations were established in southwestern Ontario from 15 June to 8 September using Mast Model M 743 meters (Mast Development Company, Davenport, Iowa, U.S.A.) fitted with SO₂ filters. Data from these sites are occasionally used to supplement the other data in drawing maps of the spatial ozone distribution.

Since scavenging of ozone in urban centres, due to higher levels of nitric oxide in cities than in rural areas, has been noted in other studies (Coffey et al, 1977), more attention has been focussed on six rural stations of Huron Park, Petrolia, Merlin, Simcoe, Orono and Stouffville.

Surface and upper air synoptic weather maps as well as computed air trajectories were assembled and analyzed with a view to relating ozone episodes to meteorological conditions.

Ozone monitoring sites in Ontario are not uniformly distributed over the province and many are located in the districts most likely to be exposed to severe air pollution. Of the 16 selected monitoring sites, 10 (Huron Park, Windsor, Sarnia, Petrolia, Merlin, London, Simcoe, Kitchener, Hamilton and St. Catharines) are located in southwestern Ontario and should be fairly representative of the rural and urban areas. In other regions, especially the northern and eastern Ontario, there are too few sites for them to be truly representative of such large areas. Nevertheless, in order to gain some idea of the spatial distribution of episodes, the following representations are hereinafter adopted: Sudbury for the northern areas, Ottawa and Cornwall for the eastern districts, and Orono, Stouffville and Scarborough for the central-southern regions.

C. GENERAL CONSIDERATIONS

Studies of atmospheric ozone near the earth's surface usually focus on the transport of ozone generated by photochemical processes from anthropogenic precursors in urban areas and of subsequent reaction of ozone precursors from distant areas. However, there are two other sources, namely, ozone transported from the stratosphere, or photochemical generation from naturally occurring precursors in the troposphere. The magnitude of each phenomenon must be determined in order to assess its contributions to the total observed surface concentration. In order to distinguish between temporary influxes of unusually high ozone concentrations lasting from several hours to a few days from natural ozone normally occurring in the surface layer of the atmosphere, background ozone concentrations were investigated.

(a) Background Ozone Levels

There is no recognized set of rules to define background ozone. In the present report it was derived from select conditions from which major sources of transported or locally generated ozone or precursors were excluded. The monthly average of the daily mean of hourly ozone concentrations as well as the monthly medians of the daily maximum of hourly ozone concentrations during daylight hours with wind direction $290^{\circ} - 10^{\circ}$ and wind speed stronger than 2.8 m/sec. for at least 7 consecutive hours were determined, to represent background ozone levels for the years 1977 - 1980. Data from 3 rural monitoring stations (Huron Park, Simcoe and Stouffville) and 1 urban site (Ottawa) were analyzed, and the results are shown in the freehand curves (b) and (c) in Figure (2). Seasonal variations are evident in both curves, with the maximum occurring in March, April or May and the minimum in October, November or December, depending on location. The high stratospheric ozone usually observed during the spring months in northern latitudes may be responsible for the occurrence of the maximum median during this season. Dütsch and Ling (1973) showed that maximum ozone was found at a height of 18 - 24 km in March and the minimum at 6 - 7 km in October over Arosa, Switzerland. However, the irregular time difference in the maximum between March at Huron Park and May at Simcoe and Stouffville cannot be fully explained. It might be due to insufficient data for these months, given the short period

of four years' data. There were few cases with northwesterly winds stronger than 2.8 m/sec. for at least 7 consecutive hours. Of course, these months are considered as meteorological transitional months in which seasonal delays, advances and rapid weather changes typically occur. Photochemical reaction involving natural precursors is considered to be only a very minor factor in the month of occurrence of maximum background concentration, since in these latitudes solar radiation is at its maximum in June, and the maximum mean mixing height at Buffalo and Flint, U.S.A. is in June and July respectively (Portelli, 1977).

The maximum values of 40 ppb at Huron Park and Stouffville may be considered the maximum background concentration in southern Ontario, since with northwest winds these sites are far removed from any anthropogenic precursors. The reading of 50 ppb at Simcoe is somewhat high and probably the result of additional ozone or precursors received from London, located only 80 km away to the west-north-west. Minimum background values at all stations varied from 19 to 27 ppb, with an average of 23 ppb.

In another approach, the monthly medians of the lowest ozone concentration during daylight hours for all days from 1977 to 1980 were abstracted, and are shown in curve (a) of Figure (2). Similar seasonal variations were found, but the monthly values were relatively lower than for curves (b) and (c). The lack of agreement stems from the fact that curves (b) and (c) were derived from selected days, while curve (a) was obtained from the total data irrespective of prevailing weather conditions. The choice of curve (a), (b) or (c) depends on the definition of background ozone concentration. It is believed, however, that curve (a) may be the most representative of a pure air mass free of abnormal ozone contamination.

(b) Annual Variation of Ozone

Ozone concentrations has a large seasonal range, particularly from summer to winter, so that "annual mean" conveys very little. However, in order to show whether the Canadian national one-year arithmetic mean maximum acceptable level of 15 ppb was exceeded or not, Table (1) gives "annual mean" ozone concentrations at selected stations in Ontario. It will be seen

that nearly all stations exceeded the criterion in each of the four years. Slightly lower averages were measured at Scarborough in 1977, 1979 and 1980 and at Sudbury in 1980. Double the acceptable level was measured at Simcoe, with 35.2 ppb in 1978 and 33.6 ppb in 1977, at Huron Park, with 30 ppb in 1977 and 1980, and at Orono, with 30 ppb in 1978.

The annual number of hours and their percentage frequency of hourly ozone concentrations exceeding certain limits are given in Table (2). While there were no occasions above 153 ppb in 1980, some were recorded for a few hours during the other three years. In 1977 Merlin had three consecutive hours on 20 July, while Orono had two hours on 4 July and one hour on 20 July. In 1978, Windsor measured 13 hours (6 on 25 May, 5 on 26 May and two on 27 May). Simcoe had 6 hours on 11 March, and Orono had 4 hours on 26 May. In 1979, ozone concentrations above 153 ppb were recorded for one hour at Orono, Scarborough and Merlin on 10 May, 11 July and 14 July respectively. Of significance here is that the air quality objective of a one-hour maximum tolerable limit above 153 ppb is apparently not limited to rural stations, but can be experienced even in urban centres, despite scavenging by nitric oxide. Concentrations above 120 ppb and above 82 ppb were registered at most stations, but with greater frequency at rural centres, as seen from Table (2).

Hourly ozone concentrations above 82 ppb persisted at times for quite a number of consecutive hours at some sites. Table (3) gives the maximum number of hours of persistence of ozone concentrations above 82 ppb at 15 stations for each of the years 1977 to 1980 inclusive. The highest number of consecutive hours (31) occurred at Simcoe on 11-12 March, 1978, followed by Cornwall (22) on 11-12 July, 1978 and Huron Park (19) on 11-12 March, 1978. Hamilton had the lowest number of consecutive hours (8) on 20 July, 1978. Of the 16 stations, 11 had the maximum number of consecutive hours in 1978, 4 sites in 1977 and zero station in 1979, and only one station in 1980. In June, 6 sites recorded the maximum consecutive hours, followed by 4 in July, 3 in March and 3 in May. To illustrate yearly variations from 1977 to 1980 Figure (3) gives cumulative annual frequencies of ozone concentrations above 82 ppb persisting for more than a certain number of consecutive hours at 4 sites representing southwestern Ontario (Simcoe), central-southern Ontario

(Orono), eastern Ontario (Cornwall) and mid-northern Ontario (Sudbury). It will be seen from Figure (3) that medians of the frequencies are about 5 consecutive hours at Simcoe and Orono, and about 4 at Cornwall and Sudbury, although the samples at Sudbury, and Cornwall are too small to give valid statistical results. The upper and lower quartiles are about 3 and 8 consecutive hours at Simcoe and Orono. This implies that for any observation taken at random the probability that it will be within this range is one-half. For Cornwall the quartiles are 2 and 8.5 consecutive hours and for Sudbury 2 and 6.5.

The year 1978 ranked first in number of hours and days, and also in severity, of high ozone concentrations, followed by 1977, 1979 and 1980. The consistent drop in severity from 1978 to 1980 was due only to fewer number of occasions of favourable meteorological conditions in 1978, and should not be considered a trend.

(c) Seasonal Variation of Ozone

Monthly values showing the seasonal variation in average ozone concentrations between 1977 and 1980 inclusive for fifteen stations are presented in Figure (4). While the yearly minimum mean monthly values occurred at all stations between November and December, when solar energy for ozone production by photochemical reaction is lowest, there was no summer month which could be regarded as typical for the maximum values. Seven sites had their maximum in July, four in May and four in June. There is no apparent relationship between radiation, proximity to the Great Lakes or major pollutant sources and the month of occurrence of the maximum. However, as expected, the mean monthly maximum was higher at rural stations than at urban sites, but this was true of the minimum at only three of the six rural stations. The highest yearly mean monthly maximum of 44 ppb occurred in July at Simcoe, and the lowest of 26 ppb also in July at Scarborough. The highest yearly mean monthly minimum of 16 ppb occurred at Orono, Simcoe and Huron Park, and the lowest of 5 ppb at Windsor. The greatest yearly mean monthly range of 29 ppb was at Windsor and the least of 20 ppb at Huron Park, Hamilton, Scarborough and Ottawa.

Table (4) summarizes the magnitude, month and year of highest and lowest monthly average daily ozone concentrations at each of the 15 locations. In the highest category, Merlin ranked first, with 63.9 ppb in July 1979, and Scarborough last with 30.0 ppb in July 1978. Ten of the fifteen stations had their highest values in July (4 in 1977, 5 in 1978 and 1 in 1979), 5 in May (1 in 1977 and 4 in 1978) and nil in June or August. Scarborough had the lowest monthly mean of 5.1 ppb in December, 1979.

To illustrate the pronounced variations in periodicity and in absolute mean monthly ozone concentration from year to year, Figure (5) gives the seasonal variation at each rural station from 1977 to 1980. It will be seen that the time of the annual maximum for individual years differed greatly from that of the four-year mean. For instance, at Simcoe, Figure (5), the four-year mean of 44 ppb occurred in July, compared with the yearly maximum in July (53 ppb) in 1977, in March (56 ppb) in 1978, in June (44 ppb) in 1979, and in June (37 ppb) in 1980. Another location, Petrolia, Figure (5c), had 3 peaks of similar magnitude in 1978 and 1980 with 40 ppb in March, 44 ppb in May, 42 ppb in August 1978 and 31 ppb in March, 32 ppb in June and 30 ppb in August 1980.

To test the effects of the Great Lakes on ozone concentrations, the six rural stations were divided into 3 groups: (1) Orono 10 km and Stouffville 25 km north of Lake Ontario; (2) Merlin 8 km and Simcoe 13 km north of Lake Erie; (3) Petrolia 24 km south and Huron Park 26 km east of Lake Huron. The seasonal mean for each group is plotted in Figure (6a). Group (2) had the highest mean, perhaps suggesting that more ozone is advected inland by lake breezes generated in the Lake Erie area than in areas around the other two lakes. However, the differences are so slight as to be ignored, being only 5-7 ppb even in the summer months. A feature of the curves in groups (1) and (2) is the pronounced arrested rise in ozone concentration during April. In group (3), in fact, there was actually a decrease, and in group (2) only a slight rise. This will be discussed later.

Combining all six rural stations, the average seasonal variation curve given in Figure (6b) shows that had the March and April values not been almost identical, a smooth sinusoidal curve could have been drawn, with a maximum in June and a minimum in November, virtually depicting the seasonal variation of solar radiation, a determining factor in generating ozone.

In order to assess the magnitude of monthly changes, the differences between successive months were derived from Figure (6b). The greatest increase, as shown in Figure (6c), was 8.5 ppb from January to February, followed by 5.5 ppb from February to March, and 5.5 ppb from April to May. The greatest decrease was 8.8 ppb from August to September, followed by 7.0 ppb from September to October. April depression might be partially due to the averaging of data for a few years containing exceptional yearly variations. It is evident from Figure (7), which plots the seasonal variations among the six rural stations for each individual year, that the 1978 April value was much lower than those of March and May at 5 of the 6 of rural stations. Simcoe, for instance, had an average of 56 ppb in March and of 53 ppb in May, in contrast to 45 ppb in April. As will be shown later in Table (16b), the number of days in 1978 with meteorological conditions favourable for the advection or generation of ozone decreased from 6 in March to 1 in April, and increased again to 14 in May. Moreover, the percentage frequency of surface winds (SE to WSW) favourable for elevated ozone concentrations decreased from 25% in March to 13% in April, and increased again to 33% in May. In 1977 ozone concentrations continued to rise from March to May at most stations, conforming to favourable meteorological conditions (March 4 days, April 6 days, May 13 days) and to percentage frequency of favourable surface winds (44% in March and 48% in April). In 1979, and 1980 seasonal ozone concentrations were generally low and had little weighting in the averaging.

Another reason for the depressed April values may be that the spring months, particularly April, are considered as meteorological transitional months in which weather systems advance so rapidly that anticyclones do not stay long enough over an area to promote stagnation which is one of the prerequisites for high ozone occurrence.

Figure (7) shows that in the winter months October to January inclusive the differences in ozone concentration were no more than 5 ppb among stations in each year, whereas in the summer months March to September there were differences in the rise and fall, and also in concentration of ozone, of as much as 23 ppb.

In Figure (8) the annual percentage frequency of hourly ozone concentrations above 50 ppb, 82 ppb, 120 ppb and 153 ppb per month are given for fifteen sites from 1977 to 1980. Monthly excesses above 153 ppb were confined to a few hours on a few isolated days only, with Windsor 0.04% (13 hours in 4 years) in May, Orono 0.03% (10 hours), 4 in May and 6 in July, Simcoe 0.02% (6 hours) in March, Merlin 0.02% (5 hours) in July, Stouffville 1 hour in May and Scarborough 1 hour in July. Excesses above 120 ppb occurred between March and September but again for a few hours on a few days only, with Orono 0.31% (105 hours in 4 years), 4 in April, 32 in May, 20 in June, 45 in July and 4 in August, followed by Windsor 0.14% (46 hours) and Simcoe 0.14% (42 hours). Other sites experiencing more than 20 hours in 4 years were Petrolia (40 hours), Merlin (36 hours), and Huron Park (21 hours). Neither Cornwall nor Sudbury recorded ozone concentrations above 120 ppb, and Ottawa had 4 hours only, 2 in May and 2 in June. Concentrations higher than 82 ppb occurred at all stations from March to September. From October to February, ozone concentrations higher than 82 ppb were experienced at only 3 stations: Simcoe 3 consecutive hours, and Merlin and Petrolia 1 hour each, all in February. Annual percentage frequencies occurred mostly in June and July, with Merlin 0.87% (230 hours) in July and Orono 0.50% (147 hours) in June. As to concentrations higher than 50 ppb, most sites recorded their maximum annual percentage frequencies in July, except for Kitchener in June and Orono in May. Simcoe had the highest annual monthly percentage frequency of 3.1% in July, and most sites recorded either no occurrence or a negligible number of hours from October to February. Merlin, Simcoe and Huron Park had 0.43%, 0.38% and 0.11% respectively in February, and Simcoe 0.14% in October.

To assess the monthly probability of occurrences of hourly ozone concentrations higher than 120 ppb and 82 ppb, the data of the six rural stations were combined to increase the sample. It is evident from Table (5) that the probabilities are extremely low, particularly for concentrations higher than 120 ppb, and would of course, have been even lower had it been possible to compute probabilities for concentrations higher than 153 ppb. In southwestern and central-southern Ontario the annual number of hours expected per month from March to September is 4 hours (probability of 0.00178) for concentrations higher than 120 ppb and 41.3 hours (probability of 0.0165)

for concentrations higher than 82 ppb, and both occurred in July. In a year, the probabilities are 10.3 hours for concentrations higher than 120 ppb and 124 hours for concentrations higher than 82 ppb.

Monthly maximum one-hour, monthly maximum day-average and monthly average ozone concentrations for fifteen stations are given in Figure (9). While the monthly averages were generally low from October to February, not exceeding 44 ppb, there were instances of maximum one-hour concentrations as high as 93 ppb in February at Merlin, 79 ppb in January at Cornwall, and 77 ppb in October at Ottawa. The maximum day-average also exceeded 50 ppb at some stations, and was as high as 60 ppb in February at Petrolia. Tropospheric or stratospheric ozone might have been the main contributors, since deep upper air troughs and strong jets, and in turn breaks in the tropopause, are more frequent at this time of the year. Figure (9) shows that the monthly variations of the maximum one-hour and the maximum day-average concentrations do not demonstrate parallel patterns. There are many occasions when a rise from month to month in the maximum day-average actually coincided with a decline in the maximum one-hour concentration. Moreover, there are large differences between the two concentrations sometimes, suggesting either that the two did not occur on the same day or else that the maximum one-hour ozone concentration persisted for a few hours only. Very high one-hour ozone concentrations were recorded during the summer months March to September, with Windsor, for instance, having 211 ppb in May 1978. Similarly with the highest maximum day-average, where Simcoe measured 116 ppb in March 1978. Table (6) gives the site and magnitude of the highest maximum day-average and the maximum one-hour ozone concentration for each month. November had the lowest maximum day-average of 47 ppb, while December had the lowest maximum one-hour ozone concentration of 57 ppb. Table (7) gives the magnitude, month of occurrence and location of the annual highest maximum day-average and yearly maximum one-hour concentration (in order of magnitude). Four sites had their highest maximum day-average in March, 2 in each of May and June, and 7 in July. Maximum one-hour concentration occurred at one station in March, at 9 locations in May, and 5 sites in July.

(d) Diurnal Variation of Ozone

The yearly diurnal variation of ozone levels for 15 stations is illustrated in Figure (10). The peak ozone level occurred between 1430 EST and 1500 EST at urban stations and about one hour later at five of the six rural stations. A secondary peak was observed between 0300 EST and 0500 EST at most urban stations, particularly from November to April, but not at any rural stations. Minimum daily ozone concentrations occurred just after sunrise at all stations, with an equal or lower secondary peak in the evening at most urban stations only. The maximum daily range was 20 ppb at Merlin and Windsor, and the minimum 6 ppb at Sudbury. The highest mean daily maximum was 41 ppb at Simcoe and the lowest 20 ppb at Sudbury. The highest minimum was 22 ppb at Simcoe and the lowest 9 ppb at Windsor.

To illustrate these interesting features of the diurnal cycle of rural and urban stations, the average monthly diurnal values are given for one rural station (Simcoe, Figure 11a) and one urban station (Ottawa, Figure 11b). At Simcoe each of the average monthly diurnal curves is smooth with no unusual undulations. The earliest daily maximum occurred in December about 1400 EST, gradually advancing to 1600 EST by June and returning to 1400 EST in December, reflecting the annual and daily solar radiation cycle, with a lag of 3 to 4 hours. The diurnal minimum occurred at about sunrise, just before the break-up of the nocturnal inversion at about 0800 EST in December and about 0630 EST in June.

The Ottawa diurnal cycle (Figure 11b) exhibited bi-modal characteristics not evident at Simcoe. Two daily ozone maxima were recorded at most urban stations. The major maximum occurred in the afternoon at all urban stations, with a time-lag of about 2 to 3 hours from the daily maximum of the radiation cycle, and a difference of 2 hours between December and June. Of interest is the occurrence of the major maximum one hour earlier at urban stations than at rural stations. The exact reason is not clear, but possibly the city heat island promotes acceleration of turbulent mixing at urban sites, two daily ozone minima were observed all year round, one in the morning and the other in the evening, as shown in Figure (11b) for Ottawa. The evening minimum was caused solely by high levels of nitric oxide

emissions from evening rush-hour traffic. The morning minimum was the usual post-sunrise occurrence, that is, similar to that at Simcoe but reinforced by morning rush-hour traffic emissions of nitric oxide. The monthly diurnal variations of nitric oxide for each month of the year for Ottawa, given in Figure (11c), support the proposition that nitric oxide was wholly responsible for the ozone minimum and partially for the morning minimum. At Simcoe the monthly nitric oxide levels are exceedingly small, 1 ppb or zero with no apparent diurnal variations, and accordingly no evening ozone minimum was observed. At Ottawa, on the other hand, there were distinct diurnal variations with the monthly morning and evening nitric oxide peaks occurring at about the same time as the morning and evening ozone minima for corresponding months, except for the February evening minimum. In December both the evening ozone minimum and the nitric oxide maximum occurred at about 1800 EST, advancing gradually to 2300 EST by June, and returning to 1800 EST in December. These occurrences lagged behind sunset from about $1\frac{1}{2}$ hours in December to about $2\frac{1}{2}$ hours in June, reflecting the more prolonged heat dissipation of the higher solar radiation in summer. As to the early-morning secondary maximum in cities, the nighttime heat island promotes turbulent mixing, which results in some downward transport of ozone from the lower boundary layer. This replenishes the ozone destroyed by nitric oxide and by contact with surfaces, and gradually increases surface ozone as the nitric oxide is diluted. Surface cooling and slackening winds as the night progresses cause a decrease in lower-level instability and in turn a slowing of the downward transport of ozone until some time between 0400 EST and 0600 EST, depending on the season, when surface ozone reaches a maximum and begins a gradual decline until the time of the usual morning minimum. Of interest is that the time of the secondary ozone maximum corresponds to that of the nitric oxide minimum. A secondary ozone maximum generated in this way, as in Ottawa, would appear less pronounced were ozone values not reduced by the reaction with nitric oxide emissions from morning rush-hour traffic. All other major urban centres (Scarborough, Hamilton, Kitchener, St. Catharines, London and Cornwall) had the secondary minimum in the evening and the secondary maximum in the early morning but with different intensities. At Windsor and Sudbury, however, they were observed from November to April only.

(e) Episodes

There is no recognized set of rules to define an ozone episode with relation to station or to critical temporal or spatial exposure levels. Schenfield et al (1980) defined an episode as a day in which elevated ozone levels above 80 ppb occurred at eight or more stations, but they did not take into consideration either duration or whether the monitoring site was rural or urban. Concord Scientific Corporation (1982) adopted the following criteria: (1) one-hour average ozone concentration should equal or exceed 82 ppb at a station on a particular day; (2) ozone concentration should equal or exceed 20 ppb for at least ten hours (including the hour or hours of the maximum level for the same station on the same day). In addition, their spatial definition was that three or more stations on the same day experience the criteria for a station-episode, and their temporal that an episode persist for two days or more at three or more stations.

In the present report, station-episode represents conditions with ozone concentrations exceeding 82 ppb for at least three hours during a specified period. To utilize results for plant injury by air pollution, a distinction was made between episodes occurring (a) during the period 1000 - 21000 EST, when plant stomata are usually open and ozone is generally high during its diurnal cycle, and (b) from 2200 - 0900 EST the following day, when plants are usually less active and ozone is generally low. These station-episode criteria were applied to each period separately, and the first, 1000 - 2100 EST, will hereafter be designated "Daylight Station Episode" (DSE) and the second, 2200 - 0900 EST, "Nighttime Station Episode" (NSE).

All NSE were associated with the same synoptic weather patterns that preceded or followed DSE. During the four years (1977-80) there were 35 NSE, 21 of which were observed at only one of the 16 sites, 7 at 2 sites, 2 at 3 sites, 4 at 4 sites, and 1 at 5 sites. Of the 35 events, 17 were associated with either pre- or post-frontal conditions, which are favourable for bringing down stratospheric ozone and breaking up nocturnal inversions. Eleven events were associated with a moderate pressure gradient, which can

result in strengthening winds and in turn the breaking-up of nocturnal inversions. There is no obvious explanation for the occurrence of the remaining 7 events, which were not associated with either a pressure gradient or frontal surfaces, and each of which occurred at one site only.

Table (8) gives the number of DSE and NSE at each site for the years 1977 - 1980 inclusive. In 1977 Merlin had the maximum number of DSE (36) and St. Catharines the maximum NSE (4), while Hamilton had zero NSE. In 1978 Orono had the maximum DSE (35) and Simcoe and Kitchener both had the maximum NSE (7). In 1979 Orono again had the maximum DSE (21) and Cornwall the maximum NSE (2). In 1980 Windsor had the maximum DSE (17) and Cornwall again had the maximum NSE (3). Figures (12) and (13) show the distribution of DSE and NSE over Ontario in four years. Surprisingly, not a single NSE occurred at any of the three sites, Scarborough, Orono, and Stouffville in the area 10 km - 65 km northeast and east of Toronto, although St. Catharines, southwest of Lake Ontario, experienced 9 occasions, and Cornwall, to the northeast along the St. Lawrence River, had 8 occasions. The absence of NSE at Orono, unexpected and inexplicable.

Table (9), which gives the monthly and yearly occasions of DSE and NSE for 16 stations for the years 1977 - 1980, shows that the monthly frequency of DSE was highest at 12 of the 16 sites in July and at 4 in June. Merlin experienced the highest number of days, 31 in July. The second highest was in May at 10 stations, including all those in the central-southern region (Orono, Stouffville and Scarborough) and in June at 6 stations, mainly in southwestern Ontario. DSE occurrences in March were limited to southwestern Ontario, with Simcoe experiencing 5 days. Sudbury recorded the least number of DSE (8) and all occurred during May, June and July. The highest monthly nighttime station episodes were at Cornwall, with 6 in June, and the second highest at Kitchener, with 5 in July. Most other monthly occurrences were within the 0 - 3 occasions range, with nil in April and one occasion at Huron Park in September.

The seasonal variations in average monthly occurrences of DSE at rural and urban stations from 1977 - 1980 are graphically represented in Figure (14). It will be seen that a lower frequency of occurrences was experienced

at urban than at rural stations in all months, with a ratio of urban to rural of 20% in March and 70% in September. The average annual number of occasions at urban stations was 10 compared to 17 at rural stations, that is, a ratio of 58%.

In order to illustrate temporal variations of daylight station episodes (DSE) and of nighttime station episodes (NSE), Table (10) gives the frequency distribution of the number of "days" of DSE and NSE persisting for three hours or more, with corresponding average daily means of ozone concentrations for 1000 - 2100 EST and for 2200 - 0900 EST, and the maximum and minimum daily mean hourly ozone concentrations (ppb) for each of these two periods for the years 1977 - 1980. There were few occasions when hourly ozone concentrations higher than 82 ppb persisted for 12 hours during the daylight hours 1000 - 2100 EST, and then only at 8 stations. Orono had the maximum, with three events in four years. For episodes longer than 3 - 10 hours, Orono again had the maximum, except for the period longer than 9 hours, when Simcoe experienced 13 occasions in four years, compared to 10 at Orono.

Sudbury, representing mid-northern Ontario, had no episodes longer than 7 hours out of a total 8 DSE, but nevertheless the mean daily ozone concentration was the highest of all the stations for 5-6-7 hour episodes. Ottawa and Cornwall, representing eastern Ontario, each had one 12-hour episode. Apart from this, Ottawa has only one 6-hour episode out of a total 6 DSE. Cornwall, however, seems to have experienced quite a number of episodes of 3 to 12 hours, with a maximum of six 9-hour DSE. As to Orono, Stouffville and Scarborough, representing central-southern Ontario, Orono, as mentioned earlier, had the maximum occasions and duration, while Stouffville had durations of 3 to 11 hours. Scarborough had one event of 11 hours, one of 10 hours, and one of 8 hours, out of 24 DSE in four years. This is low in comparison with Orono (85) and Stouffville (54), but Scarborough is, of course, an urban station. It is evident from the data for Orono and Stouffville, in particular, that central-southern Ontario may experience long, severe episodes. In southwestern Ontario all rural and urban stations had quite a number of long spells, some as long as 10 to 12 hours, except for London and Amilton, which recorded a maximum of 9 hours and 6 hours respectively. There were few nighttime station episodes, and they did not persist

for long. Simcoe, with a total of 9 NSE in four years, had one event of 12 hours and another of 8 hours. Kitchener experienced two events of 8 hours each out of total of 10 events, while Cornwall had one event of 7 hours, one of 8 hours and one of 9 hours out of a total of 8 NSE. Other NSE occurrences were of less than 7 hours' duration.

At Wesleyville, about 100 km east of Toronto in central-southern Ontario, DSE persisted for 9 days from 23 - 31 May, 1978, with a peak concentration of 171 ppb and a daily (1000 - 2100 EST) average of 118 ppb on 27 May. During this longest spell of the 4 years 1977 - 1980, Windsor and Orono each experienced 7 episode days, with a peak concentration of 211 ppb and a daily average of 140 ppb on 25 May at Windsor, and a peak of 181 ppb and a daily average of 113 ppb on 26 May at Orono. Stouffville and Merlin each had five episode days during this spell. The three-day period 26 - 28 May, and in particular 27 May, produced the severest episodes of this nine-day spell at the maximum number of stations, affecting practically all Ontario, although with less intensity in northern and eastern Ontario. On 27 May DSE were reported by 14 of the 16 stations, and on 26 and 28 by 11 stations. Even some stations which did not meet the arbitrarily assumed episode criteria registered abnormally high ozone concentrations. This 9-day spell was not included in Table 15, since Wesleyville ozone observations were taken for one year (1978) only. This spell will be discussed later.

The second longest spell was 8 DSE from 13 - 20 July, 1977 experienced at Merlin. All southwestern and central-southern Ontario was affected particularly on 14 and 20 May, when 9 stations experienced DSE each day. Table (11) gives the number of days DSE persisted at each of the 16 stations. In mid-northern Ontario (Sudbury) there was no episode longer than one day, and similarly at Ottawa, in the eastern region, although Cornwall which is also in the eastern region reported four occasions of DSE persisting for two days and one event of one day.

During both DSE and NSE, high hourly ozone concentrations were observed. Table (12) gives the peak concentrations and the number of days that certain ozone concentrations were exceeded for at least one day during DSE and NSE. During DSE, concentrations higher than 150 ppb were observed at

all stations in central-southern Ontario and at two rural and two urban sites in southwestern Ontario. Of the 16 stations, Orono had the highest number of events, 6 days Windsor and Merlin 3 days, Scarborough 2 days, and Simcoe, Stouffville and Scarborough 1 day only. Lower concentrations were recorded in eastern Ontario, with Ottawa and Cornwall having only 2 and 3 days respectively of concentrations higher than 100 ppb, although Cornwall also had 3 days between 110 ppb and 119 ppb. In general, peak concentrations were lower for NSE than for DSE. Simcoe registered the highest hourly ozone concentration (146 ppb) during one NSE, while a difference between day and night station episode peak ozone concentrations of as much as 86 ppb was observed at Windsor.

Meteorological conditions favourable for the onset of episodes (to be discussed later) did not always result in the elevation of ozone to episode levels at all stations within the area in question. However, most stations not reporting an episode did nevertheless record rising ozone, but not sufficient to persist at 82 ppb for three hours. In order to provide a fairly simple and general picture of stations affected during each day of favourable meteorological conditions in Ontario from 1977 to 1980, the cumulative average number of daylight station episodes in one year was plotted in Figure (15). Two curves were drawn, one for urban and rural stations (a) and the other for rural stations (b). It is clear from curve (a) that there was no occasion when all 16 stations reported an episode. DSE was reported on 0.25 days (annual average) at 15 stations, on 0.5 days at 14 stations, on 5.75 days at 8 stations, and on 48 days at 1 station. Curve (b), on the other hand, shows that DSE was reported on 2.5 days (annual average) at all 6 rural stations, on 14 days at 3 stations, and on 41 days at 1 station. Table (13) gives total and cumulative number of DSE occurring at a certain number of rural and urban stations for each of the years 1977 to 1980. The year 1978 ranked first, followed by 1977, 1979 and 1980.

The average monthly occurrences of daylight station episodes on the same day at more than 1, 2, 3, 4 and 5 rural stations for each of the years 1977 to 1980, as well as the monthly averages of the four years, are given in Figure (16). In 1978, March, May, June and August had the maximum number of days for all occurrences and July the maximum in 1978 and 1979. The year

1980 had the fewest occurrences at more than one and two stations, But there were no occasions at more than 3, 4 and 5 rural stations.

In order to illustrate the spatial distribution of DSE in the years 1977 to 1980, the frequency distribution of DSE at one or more stations in each district and in a combination of 2, 3 and 4 districts are shown in Figure (17). It will be seen that 93 cases occurred in the southwestern region of Ontario alone, in contrast to 10 in the central-southern, 3 in the eastern, and nil in the mid-northern district. For a combination of two districts, there were 59 cases in southwestern/central-southern districts, 1 in southwestern/eastern, 1 in southwestern/mid-northern, 1 in central-southern/eastern, nil in central-southern/mid-northern, and nil in eastern/mid-northern. In the three district combination, 19 occasions occurred in southwestern/central-southern/eastern, 4 in southwestern/central-south/mid-northern, and nil in central-southern/eastern /mid-northern. For the combination of all four districts, there were very few occasions, (3), when most of Ontario was affected. It is evident that the southwestern district had the greatest number of occasions, followed by southwestern/central-southern and southwestern/central-southern/eastern districts.

To test the longitudinal differences in DSE from west to east, the total four-year DSE were averaged for 4 stations in the extreme west, Windsor, Merlin, Petrolia and Sarnia (designated A), to the east of these stations at Huron Park, London, Simcoe and Kitchener (designated B), further east again at St. Catharines, Hamilton, Orono, Stouffville, and Scarborough (designated C), in the extreme east at Ottawa and Cornwall (designated D) and in the north at Sudbury alone (designated E). In figure (18) each area is plotted against the average four-year DSE. It is evident that there was a decrease from the extreme west to the extreme east and to the north, with B and C differing only slightly.

D. METEOROLOGICAL PARAMETERS AND OZONE

(a) Ozone and Surface Wind Direction and Speed

The group frequency distribution of specified averages of hourly ozone concentrations (ppb) during peak ozone daylight hours (1200 - 2100 EST) for the years 1977 - 1980 were prepared for eight stations (Windsor, London, Simcoe, Kitchener, St. Catharines, Hamilton, Ottawa and Sudbury), but only those for Simcoe, Windsor and St. Catharines are given in Figures (19), (20) and (21). Wind and ozone were not measured at the same site but close enough to represent the general surface atmospheric circulation of the locality.

To illustrate the average seasonal climates experienced in Southern Ontario, each year was divided into 4 three-month groups: (1) January, February, December, designated JFD; (2) March, October, November, MON; (3) April, May, September, AMS; (3) June, July, August, JJA. Wind directions were also divided into two categories: those from the N, NE, E and NW, hereafter referred to as the northerly wind component, and those from the SE, S, SW and W, hereafter referred to as the southerly wind component.

Detailed examination of the data for each group revealed that in Group 2 (MON) hourly ozone concentrations were rarely higher than 50 ppb in October and November. The highest peaks were 77 pb at Ottawa in October and 74 ppb at Kitchener in November. Simcoe had the highest number of hours (79 hours representing only 0.24% of this group) with hourly concentrations higher than 50 ppb but below 82 ppb. Thus, in Group 2 the frequency distribution for concentrations higher than 50 ppb may all be considered to have occurred in March. Petrolia recorded the highest hourly peaks in this group (129 ppb in September and 127 ppb in April for one hour only in each month), while the maximum number of hours in both April and September with hourly concentrations higher than 82 ppb was 51 hours at Petrolia (representing 0.17% of group 3) and higher than 50 ppb was 389 hours at Windsor (representing 1.1%). Thus, the frequency distribution of Group 3 may also be considered to have occurred in May.

In Group 1 (JFD), Simcoe, Merlin and Petrolia recorded hourly ozone concentrations higher than 82 ppb for 3, 2 and 1 hours respectively (0.12% of Group 1) with WSW wind direction and 11 - 20 km/h wind speed, with an hourly maximum of 89 ppb on 23 February, 1978. During this unseasonal episode other sites also recorded abnormal concentrations, that is, higher than the background levels for the time of year but less than 50 ppb. Stratospheric ozone is thought to have contributed considerably to these measured concentrations, as there was an intense upper-air trough with a strong jet over the area. In this group, ozone concentrations were rarely higher than 50 ppb, and were observed with southerly wind components, except at Simcoe and St. Catharines, where northerly wind components were also involved on a few occasions. At Simcoe there were 113 hours with ozone higher than 50 ppb, but only 7 hours were with northerly wind component, i.e. 6.2% only. At St. Catharines there was only one hour out of 5 hours, i.e. 6.7%. For concentrations higher than 82 ppb there were only 3 consecutive hours with WSW wind at Simcoe and nil at all the other 7 sites.

In Group 2 (MON), the highest seasonal percentage frequency of surface ozone concentrations above 50 ppb was observed with southerly wind components except at Ottawa, where northerly wind components were more prevalent (seasonal percentage 1.75% with northerly wind components compared to 0.5% with southerly). Simcoe had 99 hours out of 432 hours with northerly wind components, i.e. 23%, and St. Catharines 154 hours out of 490 hours with northerly wind components, i.e. 31%, which is the highest of all the stations. For concentrations higher than 82 ppb, Simcoe had 21 hours with southerly wind components out of a total of 39 hours, i.e. 53%, and St. Catharines had 2 out of 4 hours, i.e. 50%. Other sites had either nil or else all with southerly wind components. Kitchener and Windsor recorded 12 and 5 hours respectively with southerly wind components only. Concentrations above 120 ppb occurred between 10 - 12 March, 1978 at Simcoe only for 14 hours, 10 of which were with southerly wind components. Concentrations above 153 ppb occurred at Simcoe only for 6 hours with SW winds. The percentage seasonal frequencies of ozone above 82, 120 and 153 ppb were extremely small in Group 2, and all occurred in March at one or a few sites only. Of particular interest here, however, is that winds with northerly components were associated with ozone concentrations higher than 120 ppb for a significant number of hours, even though they were only about half those with southerly components.

In Group 3 (AMS), ozone concentrations above 50 ppb were largely associated with southerly wind components at all stations. However, at Simcoe, St. Catharines and Windsor in particular, there was a significant proportion with northerly wind components. Concentrations above 82 ppb were also mostly associated with southerly wind components, but the northerly components were again of significant proportion. For instance, at St. Catharines there were 23 hours with northerly components compared to 39 hours with southerly, i.e. 37%, with northerly and 63% with southerly for levels above 82 ppb. However, Simcoe had only 13 hours out of 138 hours with northerly components, and Windsor had 29 hours out of 173 hours with northerly components. Concentrations above 120 ppb were significantly higher with northerly wind components than with southerly wind components at St. Catharines, with 6 hours with northerly wind components compared to 1 hour with southerly, whereas at Windsor the southerly was higher, with 7 hours northerly out of a total northerly and southerly of 31 hours. At Simcoe one hour was recorded for each of the two directional classifications. Concentrations above 153 ppb were recorded at Windsor only, and the seasonal frequencies above this ozone level were 3 hours northerly compared to 9 hours southerly.

In Group 4 (JJA), again the southerly component was predominant at most stations for all zone ranges, except at St. Catharines, where the northerly wind components were pre-eminent, particularly at levels above 120 ppb, with the northerly wind component being 6 hours compared to the southerly 4 hours. No winds were available for Merlin or Scarborough, which recorded peaks of 167 and 165 in July.

The influence of wind speed on ozone levels is illustrated in Figures (22), (23) and (24) for Windsor, Simcoe and St. Catharines. The diagrams show the seasonal percentage frequency distributions of specified hourly wind speed classes for two wind direction groups (a) southerly wind components (SE, S, SW, W) and (b) northerly wind components (N, NE, E, NW) for given hourly ozone concentration class intervals. The most frequent and highest ozone concentrations do not seem to have occurred with very light or with strong winds but were usually associated with a relatively light to moderate flow for both wind direction groups. For the northerly wind components, hourly ozone concentrations higher than 153 ppb were observed for 3

hours at Windsor only in May with light winds (0 - 10 km/h) but with a very low percentage seasonal frequency of 0.2% of the AMS group. Concentrations higher than 120 ppb were recorded at Windsor for 8 hours in May and July with light (0 - 10 km/h) and moderate (11 - 20 km/h) winds, representing about 0.1% and 0.3%, of the AMS and JJA groups respectively. Simcoe and St. Catharines also experienced 4 and 12 hours respectively of ozone concentrations higher than 120 ppb, representing 0.2% and 0.6% respectively of the seasonal groups for ozone levels above 120 ppb. For northerly wind components, there were no occasions of ozone concentrations higher than 82 ppb with winds stronger than 30 km/h. Only 2 of 93 hours at Windsor in July and 6 of 38 hours at Simcoe in May and July, representing 0.18% and 0.49% of the seasonal frequencies respectively, were recorded in the wind class 20 - 30 km/h. Concentrations higher than 82 ppb again occurred with various wind speeds, and sometimes stronger than 40 km/h at St. Catharines, Simcoe, Kitchener and Sudbury.

Table (14) summarizes the frequency of the number of hours that surface wind at various speeds were associated with ozone concentrations above 82 ppb, 120 ppb and 153 ppb for northerly and southerly wind components between 1200 EST and 2100 EST from 1977 to 1980 at Windsor, Simcoe and St. Catharines. Wind speeds were generally lower with northerly than with southerly wind components for the three specified ozone levels at all sites. Average wind speed varied inversely with ozone concentrations except for Simcoe at the 153 ppb ozone level with southerly wind components and St. Catharines at the 120 ppb level with northerly wind components. The highest average wind speed of 21.6 km/h was recorded at St. Catharines with ozone concentrations higher than 82 ppb with southerly wind components, and the lowest of 5 km/h was at Windsor for ozone concentrations higher than 153 ppb with northerly wind components. Table 14 clearly shows that, apart from Windsor with northerly wind components, all occurrences of ozone concentrations higher than 82 ppb, 120 ppb and 153 ppb were with moderate wind speeds between 10 - 20 km/h. At Windsor the percentage frequencies within this wind class interval with southerly wind components were 78%, 83% and 52% for ozone concentrations higher than 153 ppb, 120 ppb and 82 ppb respectively.

The above surface wind analysis appears to refute the widely held view that high ozone concentrations are associated solely with southerly wind components. It seems clear that at some sites high ozone concentrations may also occur with northerly wind components, even in the summer months. These results raise the possibility that at times the major contributing factor might be local sources rather than sources originating outside Canada and brought in by long-range transport. Table 15 gives the annual number of hours of associated of ozone concentrations higher than 82 ppb and 120 ppb with various wind directions during peak daylight hours (1200 - 2100 EST) for the years 1977 to 1980 at St. Catharines, which recorded the highest ratio of occurrences of northerly to southerly wind components of the 8 stations. For concentrations above 82 ppb, the ratio of northerly to southerly occurrences was 0.37: 7 hours with easterly surface wind, 9 hours with northeasterly, and 59 hours with northerly and northwesterly. For concentrations above 120 ppb the number of hours with northerly wind components was 2.4 times those with southerly. Of the total 12 hours with northerly wind components, only 3 hours were associated with easterly winds. Emissions from Buffalo and its environs might have been the source of contaminants on occasions with easterly winds, but those with NW, N and NE winds were more likely to have been caused by emissions from the industrial areas around Hamilton and Toronto. It is possible that some occasions with NW, N and NE winds were due to the advection from non-Canadian sources of ozone and its precursors accumulated over Lake Ontario. However, examination of surface winds on some of the occasions with NW, N and NE winds reveal that northerly wind components prevailed for some considerable time prior to the rise in ozone concentrations to these high levels. Moreover, Simcoe also experienced high ozone concentrations with NW, N, NE and E winds. Possibly tropospheric and stratospheric ozone might also be involved particularly in Spring, and this will be discussed later.

(c) Maximum Air and Dewpoint Temperatures and Ozone

Monthly averages of mean daily ozone concentrations from 1200 EST to 2100 EST for four rural and five urban sites from 1977 - 1980 were plotted in Figure (25) against corresponding monthly averages of daily maximum temperatures for each of the six months April to September inclusive. S-shaped

curves were found to best represent the relationship between the two variables. It is suggested that the left end of each curve, with a low concentration, represents average background ozone levels, whereas the right end approaches what appears to be an upper limit of observed average ozone concentration in southern Ontario. Of interest is the similarity between the July and August curves and the combined July and August curve shown by Mukammal et al (1982) in their Figure (10). The present curves are somewhat steeper in the middle of the maximum temperatures ranges and less flat at both ends. These differences may be attributable to the present curves having been constructed from means of several daily average ozone concentrations for four years, while the Mukammal et al combined curve was for one year only, and each point represented one day's value. It is important to emphasize here that there is no single curve representing all months, and that the curves in Figure (25) indirectly typify air masses prevailing over most of Ontario, and may not be applicable to other areas. Better air mass representation would have been derived had upper air data been available to abstract wet bulb potential temperatures for each month. Maximum temperature is greatly affected by type, height and amount of cloud and cannot, therefore, be considered a conservative parameter in determining differences in origin of various air masses. However, in the absence of upper air data, maximum temperatures are perhaps a good second best.

Background ozone level for the averages of July and August in Figure (25) is 27 ppb at 21°C, which is very close to the 24 ppb of the Mukammal et al curve, although a large difference was found at the right end of the curve. At 31°C the present curves give about 74 ppb in contrast to 91 ppb for the Mukammal et al combined curve. As stated above, this might be due to the averaging of a large sample.

Another interesting finding in Figure (25) is that average background ozone concentration was highest in April and May, about 28 ppb, and decreased gradually to about 15 ppb in September. Examination of Figure (2), showing probable monthly background ozone levels for four sites, reveals similar trend, with a maximum between April and May, followed by a continuous decrease to November. It is possible that the maximum in April is due partly to contributions from stratospheric ozone, which is at its maximum at that time of year.

In Figure (2), three background seasonal curves (a, b and c) are given for each station (Simcoe, Stouffville, Ottawa and Huron Park). The monthly value of curve (a) for each station, representing the monthly median of the lowest daily ozone concentration during daylight hours on all days in 1977 to 1980, seems to agree fairly well with those derived from Figure (25) relating maximum temperature and average ozone. The lack of agreement of curves (b) and (c) with figures (25) stems from the fact that these curves were derived from selected days with northwesterly winds and wind speed above 10 km/h lasting at least 7 consecutive hours, while both curve (a) in Figure (2) and the curves in Figure (25) were obtained from the total data, irrespective of prevailing weather conditions. The choice of curve depends, of course, on the definition of background ozone. It is believed that curve (b) in Figure (2) may be the most representative of a pure air mass free of ozone contamination.

Hourly ozone concentrations above 153 ppb were observed at Simcoe in March 1978, when air temperature were around freezing. At the same time Merlin and Petrolia recorded hourly ozone concentrations from 121 ppb to 153 ppb, and Windsor, London, St. Catherines, Orono, Stouffville and Cornwall all had concentrations from 82 ppb to 120 ppb with maximum air temperatures between 1°C and 3°C and hourly air temperatures just below freezing. In February, Simcoe, Merlin and Petrolia recorded hourly ozone concentrations from 80 ppb to 89 ppb with air temperatures as low as -9°C. Apart from the February and March occurrences, no site recorded hourly ozone concentrations above 153 ppb, 120 ppb and 82 ppb with daily maximum air temperatures below 26°C, 23°C and 17°C respectively. Windsor recorded the highest hourly ozone concentration (211 ppb) in 4 years in Ontario with a maximum temperature of 27.4°C in 25 May 1978.

Monthly percentage frequencies of average daily ozone concentrations (1200 - 2100 EST) in various daily maximum air temperature ranges were abstracted for the years 1977 to 1980, and graphically illustrated for the 10 stations Huron Park, Petrolia, Windsor, Simcoe, St. Catherines, Stouffville, Scarborough, Cornwall, Ottawa and Sudbury, but only Simcoe is shown in Figure (27). Of interest is that neither the highest monthly average daily ozone concentrations nor the highest monthly total number. For example, in

June at Simcoe there were no occurrences of average daily ozone concentrations above 82 ppb in the highest daily maximum air temperature range of 32°C - 34°C, whereas in the lower range of 29°C - 31°C the highest monthly percentage frequency of 4.3% for June was recorded with concentrations above 82 ppb. This phenomenon was observed at all stations in different months. In May at Windsor, for instance, the highest daily ozone concentrations above 120 ppb for the month occurred in 26°C - 31°C range and not in the higher range of 31°C - 34°C, which had relatively few occasions of ozone concentrations below 120 ppb. No site recorded average daily concentrations above 153 ppb. Only a few stations experienced a few days of ozone concentrations in the 121 ppb to 153 ppb range, with Simcoe, Petrolia and Merlin recording the lowest maximum air temperature of 2°C with average daily concentrations of 151 ppb, 121 ppb and 122 ppb respectively. Windsor experienced 4 consecutive days from 25 - 28 May, 1978 with average daily concentrations of 153 ppb, 142 ppb, 126 ppb and 123 ppb respectively and maximum air temperatures of 27.4°C, 28.9°C, 30.4°C and 30.6°C respectively. Orono had only one day of 123 ppb on 26 May, 1978, with a maximum air temperature of 28°C. The highest and lowest monthly maximum air temperature with average daily ozone concentrations (1200 - 2100 EST) above 82 ppb for all 10 stations are shown in figure (26a). A wide range of maximum temperatures from 37.0° in July to 1°C in March. The lowest maximum air temperature in April was relatively high, but this might be due to only two occasions being recorded, one at Simcoe and the other at Petrolia.

Hourly ozone concentrations above 153 ppb were observed at Simcoe on 11 March, 1978, when dewpoint temperature was -4°C. In February Simcoe, Merlin and Petrolia measured hourly ozone concentrations from 80 ppb to 89 ppb with dewpoint temperature as low as -13°C. In the summer months, the highest dewpoint temperature with hourly ozone above 82 ppb was 28°C.

Monthly percentage frequencies of average daily ozone concentrations (1200 - 2100 EST) in various daily maximum dewpoint temperature ranges between 0800 EST and 24 EST were abstracted and graphically illustrated for 7 stations (Windsor, London, Simcoe, St. Catharines, Hamilton, Ottawa and Sudbury), but only Simcoe is shown Figure (28). An average daily ozone concentration of 151 ppb was observed at Simcoe with a maximum dewpoint temperature of -4°C. For monthly average daily ozone concentrations above 82 ppb,

Simcoe in July experienced the highest total days in 4 years (17 days) equivalent to 14.9% of July, of which 6.2% (the maximum) were in the 20°C - 22°C range rather than in the higher 26°C - 28°C range, which had relatively few occasions of ozone concentrations below 82 ppb. Figure (26b) gives the highest and lowest monthly maximum dewpoint temperatures with average daily ozone concentrations above 82 ppb at all stations. Here again, the lowest value in September seems too high, but it is the result of infrequent occurrences.

The above findings for both the maximum air and dewpoint temperatures do not validate the widely held view that ozone concentrations above 82 ppb, 120 ppb and 153 ppb are associated with very warm and humid air mass. While it is true that most occasions of elevated ozone persisting for 3 hours or more did occur with abnormally high seasonal maximum air temperatures and dewpoint temperatures, there were also quite a few of instances where exceptionally high ozone concentrations were experienced with either very low or just about normal temperatures and humidities. The episode of 11 March, 1978 is a good example. Air and dewpoint temperatures were about freezing or below when the highest hourly ozone concentration (171 ppb) recorded in 4 years at Simcoe was experienced. At Windsor on 30 July, 1977 ozone remained higher than 82 ppb for 8 consecutive hours with a peak of 110 ppb for two hours and an average daily concentration of 96 ppb with a daily maximum air temperature of 27.6°C compared with a normal for July of 28°C, and a maximum dewpoint temperature of 18°C, only 2°C above normal. The latter conditions cannot be described as being abnormally warm and humid for this time of year, while the high concentrations in March were possibly augmented by stratospheric ozone. As mentioned earlier, there were quite a number of days in all months and at all stations when ozone concentrations did not rise above 50 ppb, for example, even though maximum air and dewpoint temperatures reached or exceeded values at which exceptionally high ozone concentrations were recorded. Maximum surface air and dewpoint temperatures may both serve as an initial clue to air mass classification, but it must be borne in mind that the same air mass may be identified by different temperatures at different times of the year. It is only by thorough analysis of air trajectories, to be discussed below, that a pollutant-laden air mass may be identified.

(c) Air Trajectory and Ozone

Air trajectories for 1, 2, 3 and 4 days arriving at six-hourly intervals at Simcoe were calculated and plotted by computer for each day at the three levels of 1,000 mb, 925 mb and 850 mb for the years 1978 to 1980. The method and data used to calculate the trajectories were based on a model by Olson et al (1978) which used objectively analyzed gridpoint fields of meteorological variables from the Canadian Meteorological Centre. Vertical motions were computed using the "Omega" equation and combined with horizontally analyzed winds to give 3-D capacity. Some of these trajectories will be used later in the analysis of specific episodes.

Air trajectories in the horizontal and vertical give some indication of previous air motion and pressure field, which, despite some shortcomings in the results, may help to identify the source of a contaminated air mass. However, in order to be able to deal with the large mass of trajectory patterns obtained, it was necessary to select a suitable method for reducing the data for abstraction of the more common characteristics of climatological patterns. Resultant trajectories at six-hourly intervals for EST. The choice of these times is to coincide approximately with the usual beginning of the rise in, and peak times of, the ozone diurnal cycle. It is realized that the resultant flow may at times give an unrepresentative picture of the circulation. This occurs when there are any large differences in the orientations of the four flow vectors. However, there were very few such occasions during the 24 hours preceding events, and hence it is believed that the results of this procedure are valid for climatological purpose but not for day-to-day analysis. The data were further reduced by dividing the year into three four-month groups: (1) January, October, November and December; (2) February, March, April and May; (3) June, July, August and September. The percentage frequency of the seasonal and yearly occurrences of certain ozone concentrations with the resultant 24-hour flow directions were derived, and are shown in Figures (29), (30) and (31), which gives the one-day resultant trajectory of four six-hourly intervals ending at 1300 EST and 1900 EST at 1,000 mb, 925 mb and 850 mb. It will be seen from figure (29) that throughout Groups 3 (June, July, August and September) southerly wind components most frequently accompanied ozone occurrences at all the

specified levels, while the northerly wind components accounted for only about 2.2%, 0.3% and zero for concentrations above 50 ppb, 64 ppb and 82 ppb respectively at 1000 mb.

In the spring months (Groups 2), the ratios of ozone occurrences with northerly wind components at 1900 EST were 0.50, 0.13 and 0.15 of those with southerly wind components for concentrations above 50 ppb, 64 ppb and 82 ppb respectively, at 1,000 mb figure (29). These ratios increased with height, becoming 0.71, 0.56 and 1.30 respectively at 850 mb. Similar results were obtained at 1300 EST for all heights. Concentrations above 120 ppb and 153 ppb occurred on one day only, in March 1978, were accompanied by southwesterly winds and probably mostly associated with stratospheric ozone and local sources rather than with advection from distant sources from south of the border. As stated earlier, ozone concentrations were rarely higher than 50 ppb and were all associated with southerly wind components in the winter months.

The percentage frequencies of the seasonal and yearly occurrences of certain ozone concentrations with the resultant flow directions and corresponding speed ranges for one-day air trajectories ending at 1900 EST for the 1,000 mb and 925 mb levels, are shown in Figure (32) and (33). In the speed range 0 - 250 km/day, all wind directions had low seasonal frequencies of ozone occurrence during the spring months (Group 2). Westerly winds only had seasonal frequencies of 0.6% and 0.3% at 1,000 mb and 925 mb respectively with ozone concentrations above 82 ppb. Even in the summer months (Group 3), seasonal frequencies were only slightly higher (1.2%) with southerly and southwesterly winds only at 1,000 mb with ozone above 82 ppb (figure 32). Surprisingly, such light winds, which perhaps represent mostly stagnant conditions promoting high ozone levels, were not accompanied by ozone concentrations above 120 ppb and 153 ppb even at 1,000 mb and particularly in the summer months. For ozone concentrations above 50 ppb and 64 ppb the ratio of northerly to southerly wind components was as high as 1.6 at 925 mb, but only 0.5 - 0.7 at 1,000 mb in the spring months. However, in the summer months, the northerly wind component was negligible, being only 0.3% of the seasonal frequency above 50 ppb and zero above 64 ppb. In the two intermediate speed ranges of 251-500 km/day, the percentage seasonal frequency was

substantially higher than in the 0 - 250 km/day range and above 750 km/day at both 925 mb and 1,000 mb for all the specified ozone levels. In the summer months, the seasonal frequencies of ozone occurrence with northerly wind components in the two intermediate speed ranges were low, with no occurrences for ozone concentrations above 82 ppb at 925 mb and 1,000 mb. For southerly wind components, on the other hand, the seasonal frequencies were relatively high, being 13.2%, 9.1%, 3.1% and zero in the 251-500 km/day speed range and 10.3%, 4.9%, 3.4% and 0.6% in the 501-750 km/day speed range for ozone concentrations above 50 ppb, 64 ppb, 82 ppb and 120 ppb respectively. In the spring months, the seasonal frequencies of ozone occurrence with northerly wind components were significant in the two intermediate speed ranges, being 3.7%, 1.2% and 0.3% at 925 mb and 1,000 mb in the 251-500 km/day speed range for ozone concentrations above 50 ppb, 64 ppb and 82 ppb respectively. Only 2.1% of seasonal occurrences with ozone concentrations below 64 ppb were observed in the speed range above 750 km/day at 925 mb and 1,000 mb. On one day only in each of the two intermediate speed ranges, ozone concentrations above 120 ppb and 153 ppb were observed with southerly wind components in the spring months.

The above results varify the earlier conclusion in the surface wind analysis that the most frequent and highest ozone concentrations did not seem to occur with very light or strong winds, but were usually associated with a relatively light to moderate flow.

The resultant air trajectory for the 24 - 48 hours (hereafter designated 2nd day trajectory) preceding the resultant 1st day (0 - 24 hours) trajectory was derived by subtracting the resultant 1st day air trajectory from that for the 0 - 48 hours period. Figure (34) shows the seasonal percentage frequencies for the months in Groups 2 and 3 of certain ozone concentrations at Simcoe with various flow speeds and directions for the 2nd day air trajectory at the 925 mb level at 1900 EST. Comparison between Figure (34) and Figures (30) and (33) at the 925 mb level shows that the 2nd day trajectories had more occasions with northwesterly flows, greater frequencies in the lower speed ranges, and much less concentrated frequencies in the southerly flows than the 1st day air trajectories. to illustrate more clearly the difference between the 1st and 2nd day trajectories, attention was focussed

on the 36 days during which ozone concentrations were above 82 ppb at Simcoe from 1978 to 1980. Figures (35b) and (35e) show that in Group 2 (February, March, April and May) the changes in flow direction and speed were insignificant, although there was a decrease in the frequency of the northwesterly flow from 4 days for the 2nd day air trajectory to 1 day for the 1st day. However, in Group 3 (June, July, August and September), Figure (35f), the flow was generally much weaker on the 2nd day trajectory than for the 1st day. For the 29 days in Group 3, the 2nd day trajectory flow speeds were below 500 km/day on 24 days and above on 5 days, in contrast to 12 and 17 days respectively for the 1st day trajectory. Significant changes also occurred in the flow directions. Figure (35c) shows that whereas the frequencies of the 1st day resultant directions fall within a narrow range from southerly to westerly, with the southwesterly flow accounting for 76% of the 29 days, those for the 2nd day trajectory were more uniformly distributed in the southerly, southwesterly, and westerly directions, with the southwesterly occurring on only 6 days, that is, a reduction of 73% from that of the 2nd day trajectory. Figure (35a) and (35d) which combined the data from February to September show practically similar features to Group 3.

The above results reflect the large-scale motion systems. The persistent and relatively stronger southwest wind of the 1st day trajectory may have emanated from the flow in the back side of the high pressure centres moving east of Simcoe, and the relatively lighter and more variable winds of the 2nd-day trajectory from anticyclones in the vicinity of Simcoe.

E. METEOROLOGICAL CONDITIONS AND OZONE EPISODES

(a) Background

Ozone generation by photochemical processes in urban areas from anthropogenic precursors or by subsequent reaction of ozone precursors from distant and local areas are considered the main cause of the contamination of surface air by ozone. However, as stated earlier, there are two other sources, namely, tropospheric and stratospheric ozone. According to Crutzen (1974), significant rates of production of ozone in the troposphere exist as a result of several chain reactions involving carbon and nitrogen compounds, although the exact rate of downward flux of any net production to the surface cannot be determined. As to stratospheric ozone, Gidel (1980), Viezee and Singh (1980), and Wolff et al (1981) present evidence that tropospheric ozone due to the entrainment of stratospheric ozone at the break of the tropopause could contribute to total observed surface ozone. An upper air trough is a prerequisite for such zone intrusion, the extent of which depends on trough intensity as determined by the maximum wind speed at the 500 mb level. Due to lack of vertical ozone profiles and data of intensity of eddy mixing, it is well nigh impossible to calculate the contribution of stratospheric ozone to the total observed. Yet, as will be discussed later, there were occasions when high ozone concentrations occurred in conditions most favourable for the downward transport of stratospheric ozone. A case study will be presented later.

The three micro-, meso-, and macro- scales of motion govern the movement and path of the gas. Certain atmospheric motions dictate the direction and rate of bulk transport, while others generate turbulent eddies which are responsible for dilution of the gas as it moves with the mean motion.

During prolonged periods of air stagnation, ozone may be trapped in the lowest atmospheric layer, thus resulting in the build-up of abnormal concentration levels. Local effects, due to physiographical and topographical features such as lakes and semi-permanent subsidence inversions, are effective in reducing diffusion and transport of pollutants.

During summer months the area to the south and southwest of southwestern Ontario, Canada, is normally under the influence of a weak pressure configuration with very little circulation, as a result of a large amplitude ridge extending from the Bermuda High. Frequently a continental High advancing from the northwestern region of Ontario and Manitoba stagnates over Ontario and then merges with the Bermuda High. Occasionally a southwesterly flow is established behind anticyclones or ridges which move in from the west or northwest and sometimes from the southwest, bringing into southern Ontario warm and moist air which has been stagnant over southern areas for some time.

The association of high surface ozone concentrations over the lower Great Lakes basin (and indeed over much of the eastern portions of the United States), with southwesterly flows on the back sides of slow moving high pressure centres crossing eastern United States has been established in a number of studies such as Mukammal, 1965; Wolf and Liroy, 1977 Vukovich et al, 1977. In such situations an ozone river (Wolf and Liroy, 1980) stretching from the northwest coast of the Gulf of Mexico to the lower Great Lakes and on to New England is formed approximately along the air parcel trajectories, with an apparent correlation between the presence of maritime tropical air and elevated ozone. The implication is that high levels of ozone over this region are characteristic of a particular air mass and associated with accumulated emissions of a number of sources rather than individual emitters, although enhanced concentrations do occur immediately downwind of major sources. Air trajectory analyses for ozone episodes in southwestern Ontario (Chung, 1977; Anlauf et al, 1980) have shown that air parcels originated south or southwest of our region in synoptic situations identical to those favourable for formation of the ozone river. It seems reasonable to assume that the ozone problem in southwestern Ontario arises mainly from an influx of ozone-contaminated air, as was concluded by Stasiuk and Coffey (1974) to be the case for rural New York state, although some effect of local emissions was also detected by Chung (1977) northeast of the major urban centre of Toronto. Stasiuk and Coffey's (1974) work also supported the theory of a polluted air mass by showing that for episodes, ozone concentrations were uniform throughout the depth of the mixing layer (about 200 m) during the afternoon and remained high during the night at elevations above the nocturnal inversions. The persistence of high ozone concentrations above the nocturnal inversion at night was also confirmed by Ripperton et al (1976).

Stagnation does not appear to be a prerequisite for the occurrence of high ozone in the eastern United States and the lower Great Lakes basin (Vukovich et al, 1977; Wolf and Liou, 1980), although episodes may be more severe in such instances. Increases in ozone at ground level can also occur with large-scale and small-scale subsidence as a result of increased turbulent mixing below the subsidence inversion, where pollutants are usually trapped (Mukammal, 1964).

Light winds in conjunction with stagnating anticyclones over the eastern United States result in conditions favourable for the development of lake breeze along the Great Lakes. Mukammal (1964) attributed the most frequent occurrences of elevated ozone near Lake Erie to marked lake breeze surges or meso-scale discontinuity surfaces accompanied by exceptionally unstable conditions in the first 300 m above ground. He showed that Richardson's criteria between 30.5 m and 6.2 m gave high negative values (-1.5 to -2.4) at a site 2 km north of Lake Erie, although lapse rates were no higher (-0.7° to -0.8°C) than on other days. On the other hand, wind shears were exceptionally low. Tethered balloon observations indicated the existence of isothermal conditions above 60 m with shallow weak inversions from 180 m to 250 m. With such low-level stratification it is likely that small wind shears would result from convective turbulence in the isothermal layers or under inversions. With little or no downward flux of horizontal momentum from above, turbulent mixing would dissipate horizontal momentum at the surface and eventually equalize the velocities in the lower levels. The effects of lake breeze circulations on pollutant dispersal have been discussed in detail for Lake Michigan by Hewson and Olsson (1967), Lyons and Olsson (1972, 1973) and Keen and Lyons (1978). What emerges conceptually from these studies is that trapping and recirculation of pollutants within the lake breeze cell occur during the day, with stratified layers forming over the lake and a fumigation zone occurring a short distance inland where layers aloft intersect the developing thermal internal boundary layer. In the presence of a weak longitudinal general circulation, air parcels in the lake breeze circulation tend to follow a helical pattern, alternately fumigating over land and then moving offshore. At night weak land breezes tend to move pollutants offshore, where they accumulate and become part of the lake breeze circulation during the day.

Air masses associated with changes in ozone concentration in southwestern Ontario during July and August 1978 were identified by Mukammal et al, (1982). A hyperbolic function was developed relating hourly daily ozone concentration measured at several inland stations to the estimated wet bulb potential temperature of the surface mixed layer derived from upstream radio-sonde. Since no single curve represents all months, curves for the other months must be derived.

(b) Favourable Meteorological Conditions

In determining favourable meteorological conditions for the influx of photochemically generated ozone or precursors in the lower atmosphere, surface and upper air (500 mb) synoptic weather maps, together with trajectories at 1,000 mb, 925 mb and 850 mb at 1900 EST, 0100 EST, 0700 EST and 1300 EST were examined and the potential days for elevated ozone concentrations above the corresponding seasonal background levels identified. Large-scale motion systems, which can advect ozone and its precursors over distances of several hundred kilometers were investigated, together with regional and local-scale motion, such as the onset of lake breeze, causing fumigation as a result of quasi-stationary high pressure systems over the area. Occurrences of stagnation were determined on the basis of warm and cold anticyclones passing over or influencing Ontario and producing geostrophic surface winds less than 10 km/hr. Warm anticyclones are usually deep stagnating systems with high pressure prevailing far into the troposphere. In delineating the occurrence of warm anticyclones, the assumption was made that favourable conditions existed when surface high pressure prevailed far into the troposphere and persisted for three days or more. Each case was checked for either a trough or a ridge at the 500 mb level. Anticyclones prevailing for one or two days with light variable surface winds or lake breeze, and associated with either zonal flow or weak troughs at 500 mb, were listed separately as migratory anticyclones. Other synoptic conditions, such as persistent southwest winds in the back side of a slow moving high pressure centre or ridges, and the warm sector of cyclones, which often contribute to long-range transport aloft of ozone, were listed under non-stagnating conditions or advection. The last category included 17 days during the years 1977 to 1980 when frontal surfaces with troughs of strong to moderate intensity

were observed at the 500 mb level. On these occasions stratospheric and tropospheric ozone or thunderstorms might have contributed significantly to the total observed ozone, but no data were available to verify this although increased surface ozone concentration has sometimes been associated with the occurrence of thunderstorms (Mukammal 1965). Due to lack of upper air data, meteorological conditions favourable for subsidence inversions could not be identified, but they certainly must have occurred with some anticyclones. The synoptic weather conditions from February to September only were examined, because only 4 hourly ozone concentrations above 82 ppb were experienced in the other months during the four years 1977 to 1980. In October 1982 severe episodes were experienced, however, and this raises the question of the representativeness of only four years' data for yielding a sound statistical analysis.

Table (16a and b) summarizes the monthly and annual number of days and occasions during which meteorological conditions favourable for elevated ozone concentration prevailed over Ontario. Warm anticyclones meeting the above assumed criteria were very rare, with an annual mean of only 2.5 cases lasting an average of 9.5 days (Table 16a). The maximum number of days was 16 in 1978 for four occasions, two of which lasted 5 consecutive days each (25-29 May 1978 and 17-21 July 1978), and the other two for 3 days each (5-7 July and 22-24 August). Only two cases occurred in each of the years 1977, 1979 and 1980, with the longest spell in the four years being 6 days from 16-21 May, 1977. In 1979 one occasion lasted 5 days from 11-15 July, and another for 4 days (20-23 July), and in 1980 each of the two occasions lasted 3 days only (23-25 July and 25-27 August). The ratio of days with warm anticyclones to the total number of days weather conditions favourable for elevated ozone prevailed varied from 0.23 in 1978, 0.18 in 1979, and 0.15 in 1977 and 1980, with annual mean of 0.18, whereas the average annual ratio of all stagnant conditions to total favourable weather conditions was 0.55.

Korshover (1976) found that the seasonal location of stagnation centres east of the Rocky Mountains is similar to the movement of the Bermuda High. According to his distribution map of the 40-year study, the total number of stagnant cases (4 days or more) varied from about 30 cases for a total of 134 days over the extreme southwestern region of Ontario to 15 cases for a

total of 75 days just north of Toronto, down to 6 cases for 27 days further north in Ontario. Altshuller (1978) states that "the number of stagnations during the May through October period varied considerably from year to year. From as little as one stagnation of 5 days duration to as many as 10 stagnations covering a total of 57 days can occur in any one year". Thus, considering the short study period and the relaxation of our criteria to 3 days rather than 4, our results although higher than Korshover's are perhaps reasonable.

During the longest spell of daytime station episodes that persisted for 9 days from 23-31 May, 1978, warm anticyclones prevailed for 5 days, while other conditions existed during the other four days. During the next longest spell of 8 consecutive daytime station episodes from 13-20 July, 1977, only 3 days were dominated by warm anticyclones. The meteorological conditions prevailing during these two spells will be discussed later. Migrating anticyclones lasting one and two days were more frequent, than warm anticyclones with a maximum of 29 days in 1978, a minimum of 16 days in 1980, and an annual average of 22 days. The ratio of advection to all stagnant conditions varied from 0.97 in 1977 to 0.59 in 1978, with an annual mean of 0.75.

Table (16b) shows the monthly number of days favourable meteorological conditions prevailed. During 1978 there were 70 potential days of elevated ozone in contrast to 39 days in 1980. July had the maximum average number of potential days (13), followed by June, May, August, September, March and April (11.0, 9.75, 9.25, 5.25, 3.5 and 3.0 days respectively), with an annual average of 55 days. From Table 13 and Table (16b) a comparison can be made between the number of days favourable meteorological conditions prevailed in each of the four years and the cumulative number of days daytime station episodes were reported at a given number of stations. In 1977, 1978, 1979 and 1980 there were 56, 64, 38 and 36 days respectively when only one station reported an episode, in contrast to 61, 70, 50 and 39 days respectively of favourable meteorological conditions. It is clear that favourable meteorological conditions did not necessarily result in ozone episodes. However, on the identified days many rural stations did show elevated ozone concentration higher than the corresponding monthly background level, although not all reached episode and above levels. What is still difficult to

explain is the variation in intensity among stations in the same region, where sometimes one station reached episode levels while another remained slightly above background levels only.

(c) Typical Synoptic Weather Conditions with Episodes

In Ontario the maximum number of episodes occurred over an area about 80 km inland from the shores of the Great Lakes and to a lesser extent over a narrow area along the St. Lawrence River in the summer months, May to September. Evidence shows that ozone concentration generally decreased inland, particularly with stagnating anticyclones, due to upward vertical velocities and strong turbulent mixing resulting from progressive heating inland of the air. Simcoe, 10 km north of Lake Erie, experienced 70 daylight station episodes (1000 - 2100 EST) during 1977 to 1980, in contrast to only 38 days at Kitchener, about 70-80 km north of Lake Erie. Cornwall, on the St. Lawrence River, had 23 DSE compared to 10 at Ottawa, about 95 km north-east of Cornwall. Sudbury in the north had only 8 DSE. The occasions of 4 and 7 July, 1978 clearly demonstrate the decrease of ozone inland. Figure (36a) shows the diurnal variation of hourly ozone concentration, wind speed and daytime prevailing wind direction at Port Stanley, about 1 km north of Lake Erie, and at Simcoe for the episode of 7 July, 1978. Very high ozone concentrations were observed at Port Stanley, a rural station, between 1300 and 2300 EST, when hourly averages exceeded 140 ppb and peaked at 192 ppb at 1900 EST. However, lower concentrations were recorded at Simcoe, with an average hourly peak of 120 ppb at 1900 EST. Winds were light south to south-westerly at first, becoming moderate southwesterly later. Hazy conditions and only 1/10th to 3/10ths cirrus and stratocumulus clouds prevailed. This decrease in ozone concentrations inland reflected the influence of the lake circulation and the wind direction during the summer (Mukammal, 1965; Chung, 1977). In contrast to the episode of 7 July, 1978, that of 4 July, 1978 had northerly air trajectories, as shown in Figure (36b). Light northeasterly winds prevailed and similar low concentrations were experienced at both Simcoe and Port Stanley.

I. Episode of 7 July, 1978

As an example of advection conditions under which 15 of 16 sites, including all rural stations, experienced daylight station episodes, Figure (37) shows the surface synoptic weather picture at 1300 EST on 7 July, 1978 and Figure (38) gives the 500 mb chart at 0700 EST. A high pressure centre west of Illinois on 6 July moved eastwards and merged with a large anticyclone centred just off the eastern seaboard of the United States on 7 July, producing a S-SW flow to the west of the high pressure centre. At 500 mb there was a ridge to the northwest of Ontario, with a high pressure centre to the south. The wet bulb potential temperature (WBPT) at 925 mb at Flint, Michigan, U.S.A. was 23°C, typical of maritime tropical air masses which usually cross Ontario with air contaminated by ozone and its precursors (Mukammal et al, 1982). At Simcoe winds were light SSW at first, becoming moderate SW (20-28 km/hr) later. Air trajectories for 4 days at 925 mb and 1000 mb ending at St. Catharines on 7 July, 1978 at 1900 EST (Figure 39a) show that the flow at 1000 mb originated just off the eastern coast of the U.S. 4 days earlier, then passed through New York State, Pennsylvania, Maryland, and Virginia and crossed Pennsylvania again prior to its arrival at St. Catharines on 7 July at 1900 EST. The 925 mb trajectory lay just west of that of the 1000 mb level and originated southeast of Ohio 4 days earlier, then crossed Virginia, North Carolina, Kentucky and back again to Ohio prior to arriving at St. Catharines. The 24-hour resultant trajectories terminating at 1900 EST at Simcoe for 6 and 7 July 1978 for 1000, 925 and 850 mb (Figure 40) showed that on July 6 the flow was mainly SE'ly and decreased with height. On the July 7 the flow strengthened and became SSW-SW at all heights, increasing and veering with height, suggesting strong warm advection. Other air trajectories terminating at Harrow (Figure 39b), and Mount Forest (Figure 39c) show patterns similar to those for St. Catharines. Emissions of ozone and its precursors from the above industrial urban areas and from motor vehicles are bound to provide abundant sources of pollutants for contaminating air crossing the areas on its way to Ontario. The distribution of the maximum hourly ozone concentrations over Ontario for this period is given in Figure (41). All regions recorded an hourly peak of around 100 ppb, with Port Stanley registering a peak of 194 ppb. An interesting feature is the unusually high ozone recorded at Sudbury during the day

and night, reaching an hourly peak of 118 ppb at 2200 EST. Surface wind at Sudbury between 1200 and 2200 EST was moderate to strong, about 35 km/hr, gusting to 48 km/hr, and may have generated strong advection of air highly contaminated with ozone and its precursors. The air trajectory for the 925 mb level terminating at Chalk River, about 450 km east of Sudbury, at 1900 EST (Figure 39d) shows that the flow had passed over areas in the States of Michigan, Indiana and Ohio, which are usually heavily polluted.

II. Episode of 22 August 1978

The other prevalent conditions of severe episodes were quasi-stationary anticyclones causing stagnant air which had for some time been over polluted areas to become trapped under either low-level, large-scale subsidence inversions or local inversions over relatively cool lakes. Under such conditions lake breeze and meso-scale systems dominate the weather picture and become the key mechanisms by which ozone is advected inland by lake breeze and brought down to the surface by low-level turbulence. A typical synoptic weather condition is that of 22 August, 1978, when, as illustrated in Figure (42a) which gives the surface synoptic situation at 1300 EST, the centre of the high pressure was just to the south of Lake Erie and the existence of lake breeze was confirmed by the fact that winds were northerly to the south of Lake Erie and southerly to the north of the lake. The areas east of Lake Huron and north of Lake Ontario were also affected by lake breeze. Figure (42b) shows the synoptic conditions at 500 mb, where a high pressure centre lay southwest of the area, with a trough northwest of the area. Daylight station episodes occurred at 9 of the 16 permanent ozone monitoring stations and at 4 of 5 temporary monitoring stations. At Simcoe winds changed from N-NW to S-SW at about 1000 EST and surface dewpoint temperatures rose from 14°C to 17°C, while the average hourly ozone concentration jumped from 30-40 ppb to 70 ppb. Similarly at Toronto International Airport, 10 km north of Lake Ontario, where winds backed to S-SW with the onset of lake breeze and ozone increased at Scarborough from 40 ppb to 74 ppb and then later to 90 ppb at 1800 EST. The wet bulb potential temperature at 0700 EST for the 925 mb level over Flint, Michigan was 21°C, indicating a modified maritime tropical air mass over the area.

Air trajectories for 4 days at the 925 mb and 1000 mb levels terminating at St. Catharines at 1900 EST on 22 August, 1978 (Figure 43) shows that on 19 and 20 August the flow, which was moderate to strong northwesterly, passed over areas practically free of pollutants. However, on 21 and 22 August the flow at 1000 mb, which was very weak, moved in an elliptical loop, with the longest diameter about 200 km lying NE-SW, and passed over Lake Ontario, the far eastern end of New York State, northeast Pennsylvania, and remained over Lake Ontario prior to arrival at St. Catharines at 1900 EST. The 24-hour resultant trajectories terminating at 1900 EST at Simcoe for 21 and 22 August for 1000, 925 and 850 mb showed that on the 21 the flow was generally light, and varied from NE'ly at 1000 mb to NW'ly at 850, that is, the wind backed with height, suggesting cold advection. However on 22 August the flow veered and increased with height indicating the advection of warm air which lay to the right of the SW'ly flow. The flow at 925 mb displayed the same pattern but was even weaker. At 850 mb (not shown here) the flow was practically stagnant over Lake Erie during the last 36 hours. The high ozone concentration in the air parcels arriving at St. Catharines on 22 August is believed to be mostly from the stagnant air over Lake Erie, although some ozone and its precursors might also have been picked up from areas on the northern shores of Lake Erie. Figure (44a), which shows the 4-day trajectories at the 925 mb level, terminating at 1900 EST over the middle of Lake Ontario, exhibited exactly the same features as those in Figure (43), and the flow was mainly confined to Lake Ontario and Lake Erie areas during the two days. At Simcoe skies were mostly clear on 21 and 22 August, with only 2-3/10ths clouds, and maximum air temperature rose to 27°C on 22 August, despite the onset of a cool lake breeze. Such conditions provide excellent conditions for photo-chemical reactions of ozone precursors. Hourly peak ozone distribution over Ontario on 22 August, illustrated in Figure (45), is typical of such weather conditions and of ozone concentrations decreasing with distance inland from Lake Erie, Ontario and Huron, as shown by Mukammal et al (1982). On this occasion peak hourly ozone north of Lake Erie rose to 148 ppb, 143 ppb, and 132 ppb at Petrolia, Port Stanley and Merlin respectively, to 117 ppb at Dashwood near the shores of Lake Huron and 15 km west of Huron Park, and to 116 ppb at Stouffville north of Lake Ontario. Of interest here is that in eastern Ontario peak ozone concentrations hardly exceeded background levels, whereas in Sudbury ozone was

high with a peak of 70 ppb, perhaps because the pressure gradient was steep enough to cause advection. Figure (44b) shows the air trajectory at 925 mb terminating at 1900 EST at Chalk River, about 450 km east of Sudbury, and it is clear that the flow was strong during the last day and had passed over the Chicago area early on 21 August.

(d) Long Spell Episodes

The two examples given above depict meteorological conditions most favourable for the occurrence of elevated zone concentrations. To illustrate the sequence and effects of a variety of meteorological conditions on ozone distribution over Ontario, a brief summary is presented of the weather conditions prevailing during the longest spells of 8 and 9 consecutive days of daylight station episodes at at least one station.

I. Episodes of 23-31 May, 1978

The synoptic weather conditions during the nine consecutive daylight station episodes (DSE) occurring from 23 to 31 May, 1978 at Wesleyville began on 23 May with a surface high pressure centre just off the east coast of the U.S.A. (46a) and a ridge at 500 mb yielding light S-SE winds over Ontario, with only four monitoring sites (Petrolia, Stouffville, Toronto Island and Wesleyville) experiencing DSE on that day. Air trajectories for 4 days terminating at 1300 EST on 23 May at 925 mb (46b) show that the flow on 23 May was SSW about 1-15 km/hr at St. Catharines and in the middle of Lake Ontario and WSW at Chalk River. On 20, 21 and 22 May a moderate to strong N-NW flow prevailed as a result of the high pressure centre west of the area. Surface dewpoint temperatures varied from 9°C to 13°C at Simcoe and Windsor and were as low as 4°C to 6°C at Toronto. Visibility was fair to good and skies were overcast with high and medium clouds over southwestern Ontario and partly cloudy elsewhere. The distribution of the daily maximum hourly ozone concentrations (ppb) on 23 May, 1978 given in Figure (47) shows that Toronto Island had the highest at 108 ppb and Petrolia the next highest at 97 ppb, although all monitoring stations in Ontario registered concentrations above the seasonal background levels. Local rather than long-range transport of ozone may have been the major source of this isolated and mild

episode, since the trajectories did not extend very far south of the Canadian border and winds had been moderate to strong N-NW during the previous two to three days.

On 24 May a fast moving weak frontal system over Missouri moved northeast, and was centred over southern Ontario and Pennsylvania at 0700 EST, and then southeastwards lying over western North Carolina at 1300 EST (Figure 48a) with a weak trough at 500 mb. Surface winds were light variable, mainly N-NE veering to light SE at Toronto after midday, and SW at Sudbury. Dewpoint temperatures were 11°C to 14°C at Windsor and 7°C to 10°C in eastern and northern Ontario. Visibility was fair and skies were mainly clear with occasional 1/10 - 2/10ths clouds. Air trajectories at 925 mb. over southwestern and south-central Ontario (Figure 48b) show that a SSW flow passed over West Virginia, Ohio, and Pennsylvania on 22, 23 and 24 May. Under such conditions long-range transport of ozone and its precursors is likely, yet only 6 monitoring stations (Windsor, Simcoe, Scarborough, Stouffville, Toronto Island and Wesleyville) reported episodes. Distribution of the daily peak hourly ozone concentrations as given in Figure (49) show that with all monitoring stations, particularly in eastern districts, registered slightly higher concentrations than on 23 May, with Toronto Island again having the highest peak of 140 ppb. Sudbury registered an hourly peak of 64 ppb, nearly double its background level, while the air trajectory over Chalk River, about 450 km east of Sudbury figure (48b) shows a SW flow on 23 and 24 May. The air trajectory flow does not cross industrial areas, and therefore the elevated ozone may be attributed to advection from local sources, such as emissions of terpene from forested areas and oxides of nitrogen from motor vehicles and other sources.

On 25 May the eastward advance of the frontal system to the east coast of the U.S.A. caused a high pressure centre established over Wisconsin to move southeast. At 1300 EST (Figure 50a) it was centred just west of Windsor with a ridge at 500 mb just west of Ontario. Consequently, surface winds changed from light SE to light NE and then to light NW over most of Ontario, except further north, where light SW winds prevailed during the afternoon. Dewpoint temperatures dropped from 9°C to as low as 2°C at Simcoe but remained 7°C to 10°C at Sudbury. Skies were clear and visibility was good. The

air trajectories at 1300 EST at 925 mb (Figure 50b) show that the air arriving at St. Catharines and the middle of Lake Ontario had passed over Pennsylvania and Ohio two or three days earlier. Only very slight changes in peak ozone concentrations were observed, as will be seen from the distribution of hourly peak ozone concentrations on 25 May in figure (51). Six monitoring stations (Windsor, Merlin, St. Catharines, Toronto Island, Orono and Wesleyville) reported episodes. The Chalk River trajectory (Figure 50b) shows that the air did not pass over polluted areas, although Sudbury was still registering concentrations higher than its background levels. Windsor registered the highest hourly peak of (211 ppb) in Ontario of the four years 1977 to 1980. Figure (50c) gives air trajectories at 925 mb for 4 days terminating at 1300 EST on 25 May at Harrow, about 25 km SSE of Windsor. It will be seen that the air arriving at Windsor on the 25 May had passed over Detroit to the NNE, with Windsor in the direct path of urban plumes emitted in Detroit, and that, two days earlier the air had passed over the States of Ohio and Michigan, which are potential sources of ozone and its precursors. Thus, with clear skies providing ample energy for photochemical reaction, the high peak at Windsor was not surprising, although one may well ask why on this occasion and not others with almost similar conditions prevailing.

On 26 May the centre of the surface anticyclone moved very slight eastwards, lying just over Ontario at 1300 EST (Figure 52a), becoming quasi-stationary with a strong ridge at 500 mb, and promoting stagnant conditions and in turn severe ozone episodes over most of Ontario. Surface winds backed from NW to S-SE near the Great Lakes as a result of lake breeze, but changed to SW 25-30 km/hr at Sudbury, due to relatively strong pressure gradient with a warm frontal surface system lying over mid-northern Ontario. Air trajectories at 1300 EST on 26 May at 925 mb (Figure 52b) show that during the previous two days the flow was NW and hardly ever encountered heavily polluted areas, and W-SW earlier, passing over Michigan on 23 May. However, under stagnant meteorological conditions air trajectories based on a macro-scale wind regime in the layers above the surface do not give the true picture of meso-scale circulation, which dominates the weather picture below 300 m. Even air trajectories at 1000 mb terminating at 1300 EST showed a similar flow. Air trajectories at 925 mb terminating six hours later (1900 EST) at St. Catharines (Figure 52c) show a typical warm anticyclonic flow with light variable winds and NW'ly on May 26. The distribution of hourly

peak concentrations given in Figure (53) shows that exceptionally high ozone concentrations were registered at all stations, particularly those near the shores of Lake Huron, Erie and Ontario. On 26 May, 13 of 18 stations, but Sudbury or Ottawa, reported DSE mostly lasting 8-12 hours, with hourly peaks of 181 ppb at Orono, 172 ppb at Windsor and 171 ppb at Wesleyville. Lake breeze was observed at Simcoe and Toronto at about 1300 EST, when winds veered from light NW and remained light SSE for 7 hours, and dewpoint temperatures rose from 9°C to 12°C, and 14°C later. Ozone and its precursors earlier trapped under inversions over the Great Lakes must have been advected in land by the lake breeze, augmenting local sources considerably to produce such a severe episode in southwestern and central/southern Ontario. In eastern Ontario (represented by Ottawa and Cornwall) and in mid-northern Ontario (represented by Sudbury) the daily maximum hourly ozone concentrations were more than double the seasonal background level, but did not reach the episode level. The rise in ozone concentration to an hourly peak of 82 ppb might have been due to local sources and strong advection. The air trajectories terminating at Chalk River at 1300 EST and 1900 EST (Figure 52b) show the flow WSW north of the Great Lakes during the previous three days and over Wisconsin on 23 May. These areas are usually polluted, but the possibility that pollutants were picked up on route to the Sudbury area cannot be ruled out, even though local sources are more likely.

From 27 to 29 May the warm anticyclone moved slightly southeastwards, then northwards, and later westwards, producing light S-SE winds, which continued until May, when a cold front over Wisconsin began to move eastwards, producing moderate (15-20 km/hr) SE winds. The cold front passed over Windsor at 0700 EST, over Simcoe at 1400 EST and over Toronto at about 1700 EST on 31 May. Winds shifted to light northwesterly, and dewpoint temperatures dropped from 19°C to 13°C. Figure (54) shows the surface synoptic picture from 27 to 30 May. Stagnant weather conditions continued to prevail over most of southern and eastern Ontario, with daylight station episodes reported at 15, 14, 8 and 8 of 18 monitoring stations of 27, 28, 29 and 30 May respectively. The distribution of the daily maximum hourly ozone concentration from 27 to 30 May is given in Figure (55-58) respectively and show progressively lower hourly peaks after 26 May, except at Sudbury on 28 May, when hourly values above 82 ppb lasted 16 hours (not continuous) with an hourly peak of 106 ppb.

Air trajectories at 1300 EST at 925 mb over St. Catharines and the middle of Lake Ontario and over Chalk from 27 to 30 May (Figure 59) show that on 27 May the flow was typical of stagnant conditions for southern and eastern Ontario. On 28, 29 and 30 May, on the other hand, the flow crossed progressively larger industrial areas in the U.S., although the peak daily ozone concentration did not increase accordingly. This is perhaps due to less advection and weakening of the warm anticyclone, and might also demonstrate the apparently greater effectiveness of stagnant conditions as a mechanism immediately at Chalk River on 27 and 28 May (Figure 59) show that the flow passed over Michigan on 27 May and over heavily polluted Detroit on 28 May. This together with relatively strong advection resulting from the establishment of a moderate pressure gradient in areas north of Mount Forest, may explain the high ozone concentration on 28 May at Sudbury, which also recorded moderate to strong southwest winds gusting to 47 km/hr.

II. Episode of 13-20 July, 1977

The synoptic weather conditions during the eight consecutive daylight station episodes from 13-20 July, 1977 experienced at Merlin are interesting because of the series of frontal surface which crossed Ontario during this period. Unfortunately, no upper air data were available, and therefore no air trajectories were computed. The spell began on 13 July with the morning passage out of Ontario of a weak cold front, causing surface winds to veer to NW at 25 to 32 km/hr, and with a ridge of high pressure lying N-S west of the State of Michigan at 1300 EST (Figure 60a). Only Merlin recorded 5 consecutive hours of DSE, with an hourly peak of 92 ppb, while Windsor had a peak of 70 ppb. All other stations reported hourly peaks lower than 52 ppb, and therefore this episode was considered a local incident of ozone photochemically generated from precursors advected from Detroit by northwesterly winds under almost cloudless skies.

On 14 July at 1300 EST (Figure 60d), the ridge of high pressure had moved eastwards, lying NNW-SSW along a line passing through Simcoe, with a strong ridge at 500 mb. A frontal system with a warm sector just east of Lake Michigan advanced eastwards, and at about 1900 EST the warm front was

about 50 km west of Windsor Surface winds backed from light NW to light variable and then to light to moderate SSW after 0900 EST at Windsor to light SSE after 1200 EST at Simcoe and after 1900 EST at Ottawa. Visibility was 8 - 15 km over most of Ontario during the day, deteriorating at Simcoe to 4 - 6 km after 2000 EST. Skies were partly cloudy and air temperatures climbed to 32°C at Windsor but were lower, around 27°C, near the lakeshore. Dewpoint temperatures varied considerably during the day, with light variable winds, suggesting the onset of short-lived weak lake breeze at sites near the lakes. However, as the frontal system advanced, dewpoint temperature gradually rose from 16°C to 20°C by 2300 EST at Windsor, from 15°C to 18°C at Toronto and from 12°C to 15°C at Ottawa. At Simcoe, dewpoint temperatures also rose from 14°C to 19°C during the day, but for some unknown reason dropped back again late in the evening, remaining at 14°C until 0700 EST on 15 July, when they began to climb sharply, and were 24°C by 1400 EST. The distribution of the daily maximum hourly ozone concentration for 14 July, 1977 (Figure 61) shows two high ozone centres located SSW of Sarnia and of Stouffville. The first was confined to the extreme southwest of Ontario, and the second to a narrow strip over the central/southern areas. Merlin and Sarnia had 15 and 6 continuous hours respectively of ozone concentrations above 82 ppb. The former had an hourly peak of 119 ppb, while Sarnia recorded its highest hourly peak of (168 ppb) of the four years 1977 to 1980. With SSW winds at Windsor, plumes emitted from Detroit might have been responsible for the Sarnia peak ozone concentration. However, this does not explain why a record was registered this time only and not on other occasions with similar synoptic weather conditions. The long spell above 82 ppb at Merlin from 1100 EST to 0100 EST the next day may have been due to advection rather than to lake breeze. For instance at Simcoe the onset of a weak lake breeze after 1200 EST, when winds backed from light northwesterly to southwesterly 15 - 18 km/hr and dewpoint temperature rose from 16°C to 19°C, did not result in any ozone increase. Similarly with the weak lake breeze which occurred north of Lake Ontario. Orono, which usually registers increased ozone with the onset of lake breeze, was not affected either this time, recording a peak of only 15 ppb. However, Stouffville, much further inland than Orono from Lake Ontario, recorded a peak of 104 ppb at 1600 EST, due possibly to advection of ozone and its precursors from the Toronto area by southeasterly winds.

The surface weather map of 1300 EST on 15 July is given in Figure (60c). The warm sector of the frontal system lay over southern Ontario and the extreme western areas inland from Lake Ontario, while eastern and northern Ontario were influenced by the occluded portion of the frontal system. By 1900 EST the warm front had crossed Ontario and the cold front lay on a line through Sarnia, Toronto and Cornwall. A modified maritime tropical air mass, with dewpoint temperature as high as 25°C and a light to moderate southwesterly flow, prevailed over southwestern, south/central and eastern Ontario most of the day. Skies were partly cloudy at first, becoming cloudy after 1600 EST, with thunderstorms and scattered showers reported over most areas east of a line from Ottawa to Merlin. Visibility was mainly 3 - 5 km in haze and showers. The distribution of daily maximum hourly ozone concentrations on 15 July (Figure 62), show that the two high ozone centres of 14 July moved southeasterly, with one centred over Lake Erie and the other over Lake Ontario. All monitoring stations recorded high ozone peak, with an hourly peak of 152 ppb at Stouffville and of 155 ppb at Merlin which recorded ten continuous hours above 82 ppb. The advection of a modified maritime tropical air mass laden with ozone and its precursors into southwestern, south/central and eastern Ontario would seem the logical cause of this episode. However, contributions from the stratosphere and the troposphere cannot be ruled out. At the 500 mb level a trough with a fairly steep gradient for the time of year, producing winds of up to 90 km/hr, lay northwest of Ontario. This, together with the occluded front, may have caused a break in the tropospheric and stratospheric ozone to the surface.

The passage of the frontal system was followed briefly by a light northwesterly flow and a drop in dewpoint temperatures from 25°C down to 17°C - 20°C on the morning of 16 July. Another warm sector frontal system approaching southern Ontario lay on a line WNW to ENE passing just north of Sarnia and Kitchener at 1300 EST (Figure 60d), all Ontario except the extreme north was under the influence of the warm sector by 1900 EST. Surface wind backed to light SW and dewpoint temperatures rose again to 21°C - 24°C, signalling the influx into most of Ontario of a modified maritime tropical air mass. Skies were partly cloudy, clearing later at night, and visibility

was fair to good in the morning, deteriorating to 4 - 5 km in haze in the afternoon. High daily peaks of hourly ozone of 123 ppb and 100 ppb were recorded at Orono and Merlin respectively, as will be seen from the distribution of the daily maximum hourly ozone concentration for 16 July, 1977 in figure (63). The two semi-permanent high ozone centres over Lakes Erie and Ontario were located in almost the same position as on 15 July. However, they were much less intense and only Merlin, St. Catharines, Stouffville and Orono reported daylight station episodes (DSE).

From 17 to 21 July a series of frontal systems lay west and southwest of Ontario (figure f, g, h, i). Winds were light variable, moderating to SW, 10-20 km/hr later and strengthening at times to 25-35 km/hr on 20 July when Ontario was under the influence of warm sector depression. During this period an unstable modified maritime tropical air mass with dewpoint temperatures of 21°C-24°C prevailed over all Ontario, producing convective clouds, and occasional scattered showers and thunderstorms. During the nights of 20-21 July, the last cold front crossed Ontario, and winds veered to NW at 20-25 km/hr and dewpoint temperatures dropped to 11°C. Distribution of the daily maximum hourly ozone concentrations on 17, 18 and 19 July, (Figures 64, 65 and 66) shows the usual two centres of high ozone concentration over southwestern Ontario and the northern shores of Lake Ontario. It will be seen from figure (67) that the last day of the system, (20 July), produced the highest concentrations, with a peak of 176 ppb at Orono, while Merlin had its highest hourly peak of the four years 1977 to 1980 of 167 ppb. Eight stations reported daylight station episodes, and Merlin and Simcoe each recorded 12 consecutive hours of hourly ozone concentrations above 82 ppb. Long-range transport of polluted air was responsible for most of the above episodes, although again, the contribution, if any, tropospheric and stratospheric ozone brought down as a result of the frontal systems is not known.

(e) Other Interesting Episodes

I. May 31, 1977

The conditions of 31 May, 1977 are an example of an episode associated with a pre-frontal passage preceded by two days of relatively low level

ozone. The surface synoptic picture at 1300 EST on 29 May, 1977 (Figure 68a), (two days prior to the episode) shows Ontario under a ridge of high pressure, with a stationary front lying NW-SE about 100 km southeast of Windsor. Surface winds were mainly ENE 15 - 25 km/hr at Windsor and Simcoe ESE 18 - 30 km/hr at Toronto. Dewpoint temperatures at Windsor were 6°C - 9°C during the day, dropping to 4°C to 6°C at night, and at Simcoe 3°C to 5°C, falling to 0°C for two hours. Visibility was good, with partly cloudy skies, and ozone concentrations were slightly above seasonal background levels. On 30 May, a few scattered high pressure centres lay over Ontario, with a stationary front approximately west to east just south of the Province (Figure 68b). Surface winds at Toronto were mainly northeasterly 10 - 20 km/hr, and lighter at times at night, veering to ESE for a few hours, and in northern Ohio and Pennsylvania were light variable, mainly north-northeasterly. Visibility was good, and skies were partly cloudy, clearing in the evening. Dewpoint temperatures increased from the previous day, varying from 6°C in the morning to 11°C in the evening at Windsor, and from 5°C to 8°C at Simcoe and Toronto. Ozone increased to concentrations greatly in excess of background levels for short periods in isolated areas. Windsor had 97 ppb for 1 hour with wind direction 70° and wind speed 12 km/hr, and Huron Park had 91 ppb for 2 hours. Some monitoring stations along the eastern shores of Lake Ontario registered relatively high concentrations for a few hours because of the ENE winds blowing off the lake. St. Catharines reported hourly concentrations between 70 ppb and 81 ppb for 5 hours. Simcoe, with a wind speed of 20 km/hr and wind direction 40°, directly in the path of plumes emitted at Hamilton, registered 60 ppb and 63 ppb for 2 hours. All other stations recorded concentrations below 50 ppb. The surface synoptic weather conditions at 0100 EST, 0700 EST, 1300 EST and 1900 EST on 31 May, 1977 are displayed in Figure (69). At 0100 EST there was a high pressure centre southeast of Ontario and a low pressure centre with warm and cold fronts and a warm sector lay WSW of Ontario. At 0700 EST the High was quasi-stationary, but the frontal system became occluded and moved eastwards, lying about 100 km north of Windsor and causing surface winds to change from NE to light SE, moderate at times, in southwestern and south/central Ontario. At 500 mb, level at 0700 EST (Figure 70a) there was the back end of a ridge of high pressure, with light winds, over Ontario and an approaching trough to the west. At 1300 EST the surface low pressure centre lay about 175 km northwest

of Windsor. The warm front crossed Windsor at about 1300 EST, when surface dewpoint temperatures increased from 17°C to 20°C, and crossed London at about 1800 EST. AT 1900 EST, the cold front was near Windsor, and the warm front was approaching Simcoe, while the centre of low pressure was only about 50 - 70 km northwest of Windsor. At this time only a narrow strip between Windsor and Simcoe, extending about 20 - 30 km northwards, was under the influence of warm sector, which lay between Simcoe and Hamilton at 0100 EST on 1 June and had passed out of Ontario by 0700 EST. However, the occluded front was west of Mount Forest at 0100 EST on 1 June but east of Toronto by 0700 EST on 1 June. At the 500 mb level a trough lying west of Ontario (Figure 70a) at 0700 EST on 31 May had intensified by 1900 EST (Figure 70b) caused winds to strengthen as much as 130 km/hr. Skies were partly cloudy until about 0900 EST, when convective clouds began to increase, and by the afternoon skies were overcast with thunder showers developing from 1430 EST to 2200 EST at Windsor, from about 1900 EST to midnight at Simcoe, and later at Toronto. The distribution of the daily maximum hourly ozone concentrations for 31 May, 1977 Figure (71) again shows the usual two high centres of ozone concentration, one over southwestern Ontario and the other to the north of Lake Ontario. High peaks were recorded, with the highest hourly peak of the episode of 120 ppb at Huron Park at 1900 EST, when the frontal system was to the SW of the station, but the occluded front lay just a short distance to the west. Nine monitoring stations reported daylight stations episodes, with Huron Park experiencing 11 continuous hours from 1200 EST to 2200 EST of ozone concentrations above 82 ppb. The high ozone in southwestern and south/central Ontario, particularly near the lake-shore, was mainly due to advection from distant sources to the south and/or from accumulated ozone and its precursors over the lakes. However, stratospheric and tropospheric contributions are also possible, given the existence of a relatively intense trough at 500 mb, the downdraft behind the widespread thunderstorms, and the passage of the occluded front. At Windsor and London there were two ozone peaks, one between 1400 EST and 1500 EST at both sites and the other, of lower magnitude, at about 1700 EST at Windsor and of higher magnitude at London at about 1800 EST, corresponding approximately to the times of thunderstorm activity. Winds remained southeasterly throughout.

II. Episode of 10 - 12 March 1978, Episode and Stratospheric Ozone

In earlier discussion of specific episodes it was suggested that on a few occasions meteorological conditions were favourable for the entrainment of tropospheric ozone at the break of the tropopause and thus the possible contribution of tropospheric ozone to surface ozone. The most conspicuous and interesting were the unseasonal episodes of 10 - 12 March, 1978, particularly between 0900 EST on 11 March and 0900 EST on 12 March, when a number of stations in southwestern Ontario, northern Ohio, Pennsylvania and eastern New York State recorded exceptionally high ozone concentrations for several consecutive hours. Figure (72), which gives the number of consecutive hours ozone concentration was higher than 82 ppb on 11 - 12 March, 1978, shows that this episode was particularly severe along a narrow strip north and south of Lake Erie and southeast of Lake Huron. Simcoe had the highest number of consecutive hours (31), from 1000 EST on 11 March to 1600 EST on 12 March, with the highest hourly peak of 171 ppb of the four years 1977 to 1980 at the station. Other less affected areas in south/central and eastern Ontario also had concentrations much above the seasonal background level with Toronto Island, Stouffville and Cornwall recording hourly peaks of 110 ppb, 87 ppb and 85 ppb respectively.

The surface synoptic weather picture on 10 March at 1300 EST and 1900 EST in at 0100 EST, 0700 EST and 1900 EST on March 11 and 07 West on March 12, 1978 are given in figure (73). A cold front lay WSW - NNE, passing through north of Mount Forest and through Cornwall, with a low pressure centre west of James Bay (Figure 73a). Six hours later (figure 73b) at 1900 EST, the front moved slightly south as a result of the eastward movement of the low pressure centre. In the meantime a ridge of high pressure to the south pushed northwards, so that by 0700 EST on 11 March (figure 73d) Ontario was between two high pressure centres, one to the northeast and the other to the south, and also between two low pressure centres, one just south of James Bay and the other over the Atlantic, with the discontinuity surface frontalized over Ontario. At 500 mb at 1900 EST a trough with wind speeds as high as 110 km/hr lay west of the Great Lakes (figure 74a). Surface winds on 10 March were light N - NW, becoming light variable in the afternoon and WSW in the evening in southwestern Ontario but remaining NW in

south/central areas. Skies were mainly clear, becoming cloudy later in the evening. Visibility was fair to good, except at Simcoe, where it was mainly 4 - 5 km in haze. Dewpoint temperatures increased gradually from -17°C to about -4°C later in the evening, suggesting a change in air mass. The distribution of peak ozone concentrations on 10 March, (Figure 75) shows a high centre of ozone concentration north of Conneaut, Pennsylvania, with peaks as high as 129 ppb and 118 ppb at Simcoe and Huron Park respectively. Only a triangular stip of southwestern Ontario, bounded by Merlin, Huron Park, Simcoe and St. Catharines, was greatly affected by this episode with areas north of Lake Ontario only slightly affected. Toronto Island registered the highest peak in the area of 101 ppb.

With the movement of the James Bay Low slightly westwards and then northwards, its cold front moved gradually southeast, lying north of the Great Lakes at 1900 EST on 11 March (Figure 73e). At the same time, another Low with a frontal system, which was well southwest of Ontario on 10 March, moved northeast, and its warm front was lying southwest of Ontario at 1900 EST on 11 March, and the high pressure centre to the south was moving eastwards. Thus, northern and eastern Ontario were under a moderate southwesterly pressure gradient, while southwestern and south/central Ontario were under a weak pressure gradient giving mainly light S- SW winds of 8 - 12 km/hr. It was not until after 0700 EST on 12 March (Figure 73f) that the frontal system moved out of Ontario and winds changed to northwesterly. At the 500 mb level the trough steepened and began to move eastwards. Figure (74b) gives the 500 mb map for 1900 EST on 11 March, which show two strong jets converging over Ontario, one to the north and the other to the south, delineating the two frontal surfaces. Skies became overcast on 11 March and occasional snow showers were reported at Simcoe, Windsor, Sarnia and Toronto. Visibility deteriorated from 5 km to 1 km in snow and haze, air temperature rose from -5°C to 0°C . The distribution of peak ozone concentrations on 11 March, (Figure 76), shows a pattern similar to that of 10 March, except that the centre of high ozone had moved northeasterly and was centred around Simcoe, and higher ozone concentrations and larger areas to the west, east and north of southwestern Ontario were involved.

The air trajectory of 10 March showed the air flow at 925 mb terminating at Simcoe at 1900 EST (Figure 77a) had passed over Wisconsin and Minnesota on 7 and 8 March, became westerly on 9 March, crossing Lake Huron and the northern parts of the State of Michigan and Lake Michigan, and then becoming northerly during the 18 hours prior to 1900 EST, on 10 March. At 1000 mb (Figure 77b), the flow on 9 - 10 March was further south, and had passed over northern Lake Huron and northern Ontario on 7 and 8 March. The air at 925 mb did not cross heavily polluted areas, unless there was contamination over Lake Huron. Even the flow at 1000 mb terminating at Simcoe passed to the north and east of the more polluted areas. The peak ozone concentration at Sarnia was only 48 ppb, and daily solar radiation, with clear skies, was only about 17.7 MJm^{-2} . On 11 March the 4-day air trajectories at 925 mb at Simcoe at 1300 EST, Figure (77c), show that the air originated in and passed over mostly unpolluted areas on 8, 9 and most of 10 March. It was not until it crossed Lake Michigan on 11 March about 0700 EST that it was over polluted areas in the State of Michigan, including Detroit. At the 1000 mb level (figure 77d) the flow originated in northern Wisconsin, but later on 10 March it crossed practically the same areas as the 925 mb trajectory. Air trajectories terminating six hours later at 1900 EST (Figure 77e) show that the 925 mb and 1000 mb flows crossed polluted areas in Western Ohio, southwest Indiana and west central Illinois on 10 and 11 March.

The initial inference might be that low level advection of ozone and its precursors on 10 and 11 March were the cause of this two-day episode, the most exceptional March episode of the four years 1977 to 1980. However, consideration of other circumstantial evidence suggests that tropospheric and stratospheric ozone may well have played a large role. At the beginning of March solar radiation is usually low, and in the case of 11 March, 1978 with overcast skies was only 4.38 MJm^{-2} . Ozone concentrations during March rarely exceed 70 ppb and then only for a few hours, and certainly not for 31 consecutive hours above 82 ppb as observed at Simcoe. In order to demonstrate the particular conditions that prevailed during this severe episode the synoptic weather conditions and ozone distribution on 2 March, 1979 are discussed for comparison. A surface high pressure centre (figure 78a) was over Ontario on 2 March 1979 with a ridge at the 500 mb level (Figure 78b). The air trajectories at 925 mb and 1000 mb at 1300 EST and 1900 EST on 2 March, 1979, terminating at Long Point, about 40 km southeast of

Simcoe (Figure 79), show that at both levels the flow passed over areas in Pennsylvania and Ohio, which are far more polluted than those crossed on 10 and 11 March, 1978. Nevertheless, ozone concentration did not rise above 47 ppb. Had the synoptic weather conditions of 2 March, 1979 occurred later in the year, a severe episode would certainly have been experienced. Surface weather observations resembled those of the episode of 11 March, 1978. Air temperatures were near freezing, the ground was covered with snow, and visibility was 2 - 3 km in haze and fog.

It is suggested that the synoptic weather picture on 10 and 11 March, 1978, as evidenced by frontal surfaces, strong jets and an intense upper air trough, was most favourable for a break in the tropopause and the bringing down of stratospheric ozone into the troposphere and then to the surface. It might be countered that a large contribution of stratospheric ozone is unlikely having regard to the high nephelometer measurement of the light scattering coefficient from atmospheric particles at Toronto Island (Ahmed et al, 1980). Values as high as $292 \text{ BSCAT} \times 10^6, \text{ M}^{-1}$ were measured on 11 March, 1978, suggesting that the air was dirty and perhaps contained precursors for photochemical production of ozone. However, high nephelometer measurements are not necessarily indicative of high ozone. On 24 August, 1978, for instance, nephelometer measurements at Toronto Island were as high as 470 units, and yet ozone did not rise above 32 ppb.

It is worth mentioning here that there were a few occasions in September with meteorological conditions, such as intense troughs and strong jets at the 500 mb level, and surface fronts, favourable for a break in the tropopause, but ozone increased only slightly above its seasonal background level. No satisfactory explanation can be advanced, except that stratospheric ozone is at its lowest values during fall months, but it is not clear how significant this is.

F. SUMMARY AND CONCLUSION

From such analysis as is possible with the limited data available, certain significant features of ozone episodes have been identified. However, it has not been possible in this report to cover the many complexities related to transport mechanisms, sources and distribution of ozone, but it is hoped that this discussion will lead to new and improved studies to further elucidate the many aspects of oxidant climatology. The problems of concern are those dealing with insufficient rural monitoring stations, scarcity of data in areas east of Toronto and north and east of the Great Lakes, and also lack of meso-scale and upper air meteorological and ozone data. Superimposed on these difficulties are several factors involving space and time variability, and these may be associated with the conditions of emission and locality or with atmospheric behaviour on large and small scales. In general, it was possible to characterize the various weather conditions associated with elevated ozone, but there was less scope for obtaining discriminating statistical analyses, since they were drawn from only four years' data. Neither chemistry nor impact is dealt with in this report.

It is of interest to remark here that while the results show that annual frequencies of high damaging ozone levels in Ontario are low and sometimes even limited to a few hours only, a single episode is nevertheless sufficient to destroy certain crops and damage forests, provided high ozone conditions are coupled with other pre-requisites such as susceptible stages of plant development, presence of a mechanism for bringing down ozone to the surface, and other micro-meteorological and physiological factors favourable for intake of ozone by the vegetation. Over the four years 1977 to 1980 studied, only one monitoring station in Ontario, Windsor, recorded one hour of ozone concentration of 211 ppb, which is slightly above the human tolerable level of 200 ppb for one hour tentatively recommended by Canadian Federal - Provincial Committee on Air Pollution. However, hourly ozone concentrations higher than 200 ppb were reported by Anlauf et al (1975) in several instances in August 1975 at Toronto Island. Background ozone concentrations displayed distinct seasonal variations at all stations, the maximum occurred in March, April or May and the minimum in October, November or December. The high stratospheric ozone usually observed during the spring months in

northern latitudes may be responsible for the occurrence of the maximum during this season, and the low solar energy in October, November and December may partly account for the minimum. The maximum value of 40 ppb and the minimum value of 23 ppb derived from selected days with wind directions N - NW and wind speed stronger than 2 - 8 m/sec for at least 7 consecutive hours may be considered to represent the background levels in southern Ontario, since with such wind conditions the monitoring sites are far removed from any significant anthropogenic precursors.

Ozone concentration has a large seasonal range, particularly from summer to winter, so that "annual mean" conveys very little. However, in each of the four years, nearly all stations exceeded the Canadian National one-year arithmetic mean maximum acceptable level of 15 ppb. Monthly one-hour ozone concentrations above the maximum tolerable level of 153 ppb were confined to a few hours on a few isolated days only. Of interest is that the air quality objective of a one-hour maximum tolerable limit is apparently not limited to rural stations but can be experienced even in urban centres, despite scavenging by nitric oxide. However, neither north-central Ontario (represented by Sudbury) nor eastern Ontario (represented by Ottawa and Cornwall) recorded concentrations higher than 153 ppb. Concentrations above the maximum acceptable level of 82 ppb occurred at all stations from March to September. The monthly maximum hourly probabilities above 100 ppb and above 82 ppb were 1.78×10^{-2} and 1.65×10^{-2} respectively in July, followed by 7.5×10^{-4} and 9.0×10^{-3} in May. In a year the probabilities are 10.3 hours for ozone concentrations higher than 120 ppb and 124 hours for concentrations higher than 82 ppb. Hourly ozone concentrations above 82 ppb persisted at times for quite a number of consecutive hours at some stations. The highest number of consecutive hours (31) occurred at Simcoe, followed by Cornwall (22) and Huron Park (19). The year 1978 ranked first in number of hours and days and also in severity of ozone concentrations, followed by 1977, 1979 and 1980. The consistent drop in severity from 1978 to 1980 was due only to fewer occasions of favourable meteorological conditions in 1978, and should not be considered a trend.

The greatest increase in average monthly ozone concentrations from month to month was 8.5 ppb from January to February, followed by 5.5 ppb from February to March and 5.5 ppb from April to May. The greatest decrease was 8.8 ppb from August to September, followed by 7.0 ppb from September to October. The depressed average ozone concentration in April was shown to be partially due to averaging of data over a few years with exceptional yearly variations.

The monthly and yearly diurnal variation of ozone levels at urban stations exhibited bi-modal characteristics not evident at rural sites. Two daily maxima and minima were recorded at urban stations, but only one maximum and one minimum at rural stations. The second minimum in the evening at urban station was shown to be caused solely by high levels of nitric oxide emissions from evening rush-hour traffic. Morning rush-hour traffic emissions of nitric oxide may also have lowered the normal morning minimum. As to the early-morning second maximum in cities, the nighttime heat island, which promotes turbulent mixing and in turn downward transport of ozone from the lower boundary layer, was considered the main cause of this phenomenon. Of interest is that the time of the secondary ozone maximum corresponds to that of the nitric oxide minimum.

Analysis of surface wind during peak ozone daylight hours (1200 - 2100 EST) appears to refute the widely held view that high ozone concentrations are associated solely with southerly wind components (SE, S, SW and W). At several sites, particularly St. Catherines, the frequencies of northerly wind components (NW, N, NE and E) were significant in May and at times even in June, July and August. At Windsor there were 12 hours with hourly ozone concentrations higher than 153 ppb in May (1977 - 1980), 3 of which were with northerly wind components. At St. Catherines concentrations above 120 ppb during June, July and August (1977 - 1980) occurred for 10 hours, 6 of which were with northerly wind components, while in May there were 7 hours, 6 with northerly wind components. For concentrations above 82 ppb the ratio of northerly to southerly wind components was 0.27. The most frequent and highest ozone concentrations do not seem to have occurred with very light or with strong winds but usually were associated with a relatively light to moderate flow.

During 1977 to 1980 the yearly and monthly frequencies of ozone concentrations exceeding 82 ppb for 3 consecutive hours and more during daylight hours (1000 - 1200 EST), designated DSE, and nighttime hours (2200 - 0900 EST), designated NSE, are tabulated. Windsor and Orono recorded the maximum DSE occurrences (85) in 4 years, while Sudbury experienced the minimum (8). As to NSE, Kitchener reported the maximum (10), but inexplicably not a single occasion occurred at any of the three sites in south/central Ontario, although Cornwall in eastern Ontario had 8 occasions. The highest monthly frequency of DSE was in July, with Merlin experiencing the maximum number of occasions (31). The longest spell of DSE occurred at Wesleyville with 9 consecutive days in May 1978. Spatial frequency distribution of DSE in 4 years at one or more stations in each of four Ontario districts and in a combination of one, two, three and four districts shows that the highest number of occasions in one district alone was 93 in southwestern (district 1), in contrast to 10 in central-southern (district 2), 3 in eastern (district 3) and nil in mid-northern (district 4). There were only 3 cases when all four districts experienced episodes on the same day. In the three-district combination, 19 occasions occurred in districts 1, 2 and 3, four occasions in districts 1, 2 and 4, and nil in districts 2, 3 and 4. For a combination of two districts, there were 59 cases in districts 1 and 2, and in districts 1 and 3, one in districts 1 and 4, one in districts 2 and 3, and nil in districts 2 and 4 and 3 and 4. In general there was a decrease in episodes from the extreme west to the extreme east and to the north.

Maximum air and dewpoint temperature analyses do not validate the widely held view that ozone concentrations above 82 ppb, 120 ppb and 153 ppb are associated with very warm and humid air masses. There were quite a few occasions when exceptionally high ozone concentrations were experienced with either very low or just about normal temperatures and humidities. A wide range of maximum temperatures from -5.7°C to 37.0°C and dewpoint temperatures as low as -13°C were experienced with hourly ozone concentrations above 82 ppb. Simcoe recorded an hourly ozone concentration of 171 ppb with air and dewpoint temperatures of -1°C and -5°C respectively.

One-day resultant air trajectories at four six-hourly intervals ending at 1300 EST and 1900 EST at 1000 mb, 925 mb and 850 mb show that ozone concentrations were most frequently associated with southerly wind components

in the summer months. The ratios of northerly to southerly winds components were 0.07%, 0.02%, and 0.0% for ozone concentrations above 50 ppb, 64 ppb and 82 ppb respectively at 1000 mb and 925 mb, but increased considerably to 0.50%, 0.31%, and 0.15% respectively in the spring months. In the winter months ozone concentrations above 50 ppb were associated with southerly wind components. The trajectory results verify the conclusion in the surface wind analysis that the most frequent and highest ozone concentrations were associated with relatively light to moderate flows and not with very light or with strong flows. The 0 - 24 hours and the 24 - 48 hours resultant reflected large-scale motion systems. The persistent and relatively stronger southwest wind of the 0 - 24 hours trajectory may have emanated from the flow in the back side of the high pressure centres moving east of Simcoe, and the relatively lighter and more variable winds of the 2-days trajectory from anticyclones in the vicinity of Simcoe.

Although there were several recognizable meteorological regimes associated with elevated ozone concentrations over Ontario, those with weak pressure gradients favourable for the onset of lake breeze or with southwesterly flows on the west side of slow-moving high pressure centres crossing the eastern United States were the most frequent and resulted in the highest ozone concentrations. The majority of episodes of abnormally high ozone concentration followed the advection of a modified maritime tropical air mass or sometimes modified maritime polar air mass, which may be identified by the seasonal wet bulb potential temperatures of the surface mixed layer.

Higher ozone concentrations were found near the shores of the Great Lakes as a result of thermally induced lake breezes or stable marine layers due to relatively cool lake surface water temperatures, particularly during the summer months. Pollutants injected into such flows show limited mixing while over the lakes but give rise to a fumigation zone a short distance inland. In the case of lake breezes, these pollutants may be recycled several times. A distinctive feature of the distribution of the daily maximum hourly ozone concentrations of all episodes examined was the presence of high ozone centres over the Great Lakes, particularly Erie and Ontario.

Ozone maxima over Ontario may mostly be attributed to long-distance transport of emissions from major industrial areas south of the border. However, local, tropospheric and stratospheric contributions cannot be ruled out and may even be a major source at times. Many air trajectories 12 - 36 hours prior to severe episodes show that the air had passed over the Great Lakes, particularly Lake Erie, but had not earlier crossed heavily polluted areas. In such circumstances ozone and its precursors accumulated over the lake must have been the major source. However, local Ontario sources must also have contributed, due to land breeze and the predominance of northerly wind components a day or two prior to the onset of the southerly wind component. Certainly along the north shore of Lake Ontario, and possibly the east shore of Lake Huron, local sources are likely the major contributors to the ozone maximum. As to tropospheric and stratospheric ozone, the examples given show that there were occasions, particularly in the spring, when meteorological conditions were most favourable for the entrainment of stratospheric and tropospheric ozone at the break of the tropopause, which could have contributed to total observed surface ozone. However, due to lack of vertical ozone profiles and data of intensity of eddy mixing, it is well nigh impossible to calculate the contribution of stratospheric and tropospheric ozone to the total observed ozone. Meteorological conditions favourable for elevated ozone concentration over Ontario show that warm anticyclones persisting for three days or more were very rare, with an annual mean of 2.5 cases lasting an average total of 9.5 days. However, the annual mean of all stagnant conditions including warm anticyclones and migrating Highs lasting one and two days was 3.5 days, in contrast to non-stagnating conditions or advection of 23.5 days, i.e. stagnant conditions were 1.34 times those of non-stagnating conditions. The year 1978 had the maximum number of days (70) favourable for elevated ozone, while 1980 had the minimum of 39 days. The highest average monthly number of favourable days (13) occurred in July, while the average annual was 55 days. Favourable meteorological conditions did not necessarily result in ozone episodes. However, on the identified potential days many rural stations did show ozone concentrations above the corresponding monthly background level, although not all reached episode and above levels. What is still difficult to explain is the variation in intensity among stations in the same region, where sometimes one station reached episodes levels while another remained slightly above background levels only.

Eighty-five episodes were examined but only 23 are presented in this report to illustrate the sequence and effects of a variety of meteorological conditions on ozone distribution over Ontario.

G. RECOMMENDATIONS

Lack of critical data and gaps in present knowledge have frequently made it necessary to speculate on rather than specify the actual sources, transport and distribution of ozone. Unless these limitations are removed, it will be extremely difficult to provide decisive guidance in improved assessments of air quality. The following recommendations focus mostly on the meteorological aspects of the problems.

1. Although ozone monitoring has been underway for years, the current network coverage is so inadequate that it is very difficult to determine the exact ozone distribution in areas more than a few kilometres inland from Lake Erie and eastern Lake Ontario, and even so most of the stations are centred in urban areas. Thus, an improved monitoring network, particularly in rural areas and in eastern and northern Ontario, is highly recommended to determine with confidence the present status and trends in air quality. In this connection, field surveys of ozone damage to vegetation have a definite place in the assessment of ozone distribution. Certain limitations of this technique have to be recognized. The first limitation is in our ability to recognize and identify the ozone effect. Secondly, we are dependent on the existence of susceptible plant or crop varieties in a susceptible stage of development. Thirdly, knowledge of dose and effect is mandatory, and fourthly, competent observers capable of recognizing symptoms of damage must be made available in the field. Recognizing the above limitations, the use of plants as tracers of atmospheric transport and dilution is of great interest to the meteorologist, as observations of plant damage and meteorological conditions may assist in identifying sources.
2. Lack of data on atmospheric stratification and wind measurements in the first 300 metres has often hampered analysis. It is therefore recommended that routine mini-sonde observations at a few key stations be initiated at rural and urban stations. In this connection, ozone measurements at a height of about 300 - 500 metres above ground, such as at the CN tower, be started at one, two or more sites.

3. Major problems were encountered in explaining the variations in ozone intensities among stations in the same region, where sometimes one station reached episode levels while another nearby site remained slightly above the background level only. This phenomenon occurred even between rural stations. In other instances it was difficult to ascertain the extent of the influence of lake breeze pulsations or meso-scale discontinuity surface on local and regional ozone sources and distribution. Definite progress can only come from theoretical and full-scale ad hoc experimental work for short durations with meteorological conditions favourable for severe episodes to develop models more suitable for handling meso-scale and local problems and to assess ozone stratification over the Great Lakes.
4. Uncertainties about stratospheric and tropospheric ozone contributions to surface concentrations must be resolved. There is evidence that on some occasions significant contributions may be attributed to upper air sources. Thus, support research field programmes are urgently needed using ozone-sondes and other supporting meteorological data at few sites for a few days prior to and following meteorological conditions favourable for a break in the tropopause. This would enable the procurement of sufficient observations to draw ozone trajectories at different levels for different location.
5. Studies of the variations in daily ozone concentrations with seasonal wet bulb temperatures in the surface mixed layer similar to those of Mukammal et al (1982) should be undertaken. The inclusion of such a study in this report was contemplated, but it was not possible due to unavailability of reliable upper air data. Thus, AES should acquire from the U.S. Weather Bureau upper air data sets of all stations of interest for such analysis.
6. In the analysis of air trajectories there were occasions when the model accelerated the movement of the pressure fields, particularly in stagnant conditions. It is therefore recommended that the Olsen et al model be re-examined and perhaps allowance made for frictional effect.

7. Ozone poses a serious threat to agriculture, forestry, industry and health. Individual studies on its impact on agriculture have been conducted periodically over the past quarter of a century. Interesting and useful results have been obtained, but as yet no comprehensive information is available on the economic losses to Canadians. Thus, it is highly recommended that studies be initiated immediately on damage assessment and the relationship between dose and response in the natural environment under favourable meteorological conditions.

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Table (1) Annual Mean Ozone Concentration At Selected Stations in Ontario

Location	1977			1978			1979			1980			1977 - 1980		
	Annual mean (ppb)	Percent- age of data valid	Annual mean (ppb)	Percent- age of data valid	Annual mean (ppb)	Percent- age of data valid	Annual mean (ppb)	Percent- age of data valid	Annual mean (ppb)	Percent- age of data valid	Annual mean (ppb)	Percent- age of data valid	Annual mean (ppb)	Percent- age of data valid	Annual mean (ppb)
Huron Park	29.6	(65.0)	29.8	(96.7)	25.9	(78.2)	23.6	(98.0)	27.2	(84.5)					
Windsor	20.6	(96.8)	18.0	(97.4)	15.7	(92.7)	19.9	(92.8)	18.5	(94.9)					
Merlin	28.3	(48.0)	28.2	(93.7)	24.7	(71.4)	23.6	(87.4)	26.2	(75.1)					
Sarnia	27.5	(96.5)	21.5	(96.7)	23.2	(96.0)	21.6	(97.5)	23.5	(96.7)					
Petrolia	26.5	(81.4)	29.3	(82.5)	27.2	(85.3)	22.3	(96.1)	26.3	(86.3)					
London	20.9	(86.8)	20.5	(97.9)	16.6	(95.9)	18.5	(94.7)	19.1	(93.8)					
Simcoe	33.6	(91.6)	35.2	(95.8)	28.1	(95.8)	26.3	(94.5)	30.8	(94.4)					
Kitchener	24.9	(89.1)	27.6	(89.6)	20.5	(86.8)	20.7	(97.3)	23.4	(90.7)					
St Catherine	22.1	(96.1)	24.0	(98.2)	18.8	(75.2)	20.8	(94.7)	21.4	(91.1)					
Hamilton	16.6	(99.1)	16.3	(95.3)	15.3	(96.6)	17.4	(96.8)	16.4	(97.0)					
Scarborough	14.9	(97.6)	17.2	(98.6)	14.4	(94.1)	13.8	(94.4)	15.1	(96.2)					
Orono	27.5	(97.6)	30.1	(94.8)	26.8	(99.2)	26.4	(44.3)	27.7	(84.0)					
Stouffville	25.7	(95.3)	28.9	(99.5)	24.2	(92.9)	22.8	(87.8)	25.4	(93.9)					
Ottawa	19.2	(95.9)	19.2	(88.5)	17.2	(96.6)	15.4	(90.1)	17.7	(92.8)					
Cornwall	18.7	(97.0)	25.7	(98.2)	23.4	(86.1)	24.8	(93.4)	23.1	(93.7)					
Sudbury	17.5	(88.1)	18.0	(97.8)	18.3	(97.3)	13.9	(97.2)	16.9	(95.1)					

Table (2) Annual number of hours (bracketed figures) and the percentage hourly frequency (unbracketed figures) for which ozone concentrations (ppb) exceed certain limits

	1977					1978					1979					1980					1977-1980				
	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
Huron Park	5690	(868)	(142)	(4)	(-)	6853	(953)	(166)	(14)	(-)	6853	(465)	(55)	(3)	(-)	8606	(461)	(33)	(-)	(-)	29624	(2747)	(396)	(21)	(-)
Windsor	8479	(720)	(231)	(13)	(-)	8532	(464)	(196)	(34)	(13)	8120	(407)	(53)	(-)	(-)	8152	(701)	(128)	(3)	(-)	33283	(2752)	(591)	(50)	(13)
Merlin	4209	(723)	(188)	(19)	(4)	8204	(999)	(181)	(9)	(-)	6254	(372)	(31)	(4)	(1)	7673	(560)	(47)	(4)	(-)	26340	(2634)	(447)	(36)	(5)
Petrolia	7130	(776)	(155)	(10)	(-)	7227	(950)	(229)	(22)	(-)	7470	(682)	(122)	(6)	(-)	8443	(396)	(32)	(2)	(-)	30270	(2804)	(539)	(40)	(-)
London	7604	(550)	(56)	(-)	(-)	8578	(601)	(83)	(-)	(-)	8405	(322)	(35)	(-)	(-)	8320	(432)	(41)	(-)	(-)	32907	(1905)	(215)	(-)	(-)
Simcoe	8025	(1480)	(198)	(4)	(-)	8392	(1916)	(304)	(36)	(6)	8394	(806)	(75)	(2)	(-)	8301	(624)	(33)	(-)	(-)	33112	(4826)	(610)	(42)	(6)
Kitchener	7804	(732)	(34)	(-)	(-)	7845	(996)	(230)	(4)	(-)	7606	(450)	(46)	(-)	(-)	8549	(638)	(41)	(-)	(-)	31804	(2806)	(361)	(4)	(-)
St. Catharines	8414	(756)	(88)	(4)	(-)	8603	(940)	(167)	(5)	(-)	6588	(333)	(6)	(1)	(-)	8317	(543)	(51)	(5)	(-)	31922	(2572)	(312)	(15)	(-)
Hamilton	8680	(312)	(7)	(-)	(-)	8348	(397)	(62)	(-)	(-)	8463	(282)	(23)	(-)	(-)	8503	(369)	(21)	(-)	(-)	33994	(1360)	(113)	(-)	(-)
Scarborough	8549	(246)	(12)	(-)	(-)	8634	(498)	(98)	(3)	(-)	8244	(282)	(38)	(3)	(1)	8288	(198)	(17)	(-)	(-)	33715	(1124)	(165)	(6)	(1)
Orono	8552	(773)	(178)	(14)	(3)	8304	(997)	(230)	(22)	(4)	8690	(717)	(254)	(19)	(3)	3893	(184)	(37)	(4)	(-)	29439	(2691)	(699)	(59)	(10)
Stouffville	8349	(636)	(71)	(9)	(-)	8713	(1366)	(170)	(2)	(-)	8136	(542)	(79)	(4)	(1)	7716	(276)	(30)	(3)	(-)	32914	(2820)	(352)	(18)	(1)
Ottawa	8404	(334)	(11)	(-)	(-)	7749	(352)	(58)	(4)	(-)	8458	(219)	(8)	(-)	(-)	7911	(81)	(2)	(-)	(-)	332522	(988)	(79)	(4)	(-)
Cornwall	8495	(203)	(5)	(-)	(-)	8606	(954)	(135)	(-)	(-)	7541	(534)	(51)	(-)	(-)	8208	(405)	(51)	(-)	(-)	32850	(2096)	(242)	(-)	(-)
Sudbury	7718	(228)	(14)	(-)	(-)	8568	(381)	(37)	(-)	(-)	8522	(347)	(16)	(-)	(-)	8334	(82)	(-)	(-)	(-)	7152	(1028)	(67)	(-)	(-)

A = No. of hours of valid observations, B = above 50 ppb, C = above 82 ppb, D = above 120 ppb, E = above 153 ppb.

(Table 3) Maximum number of consecutive hours ozone concentrations persisted above 82 ppb at selected stations in Ontario

Station	1 9 7 7			1 9 7 8			1 9 7 9			1 9 8 0			1977 - 1980		
	Number of consecutive hours	date	Number of consecutive hours	date	Number of consecutive hours	date	Number of consecutive hours	date	Number of consecutive hours	date	Number of consecutive hours	date	Number of consecutive hours	date	Number of consecutive hours
Huron Park	14	21/5	19	11-12/3	12	21/7	7	27/8	19	11-12/3/78			19	11-12/3/78	
Windsor	14	21/5	14	29/5	10	8/7	15	23/6	15	23/6			15	23/6/80	
Merlin	15	14/7	14	11-12/3	10	24/7	13	23/6	15	23/6			15	14/7/77	
Petrolia	15	21/5	17	11-12/3	11	16/6	7	26-27/8	17	11-12/3/78			17	11-12/3/78	
London	8	17/5	12	7/6	9	22/7	8	26/6	12	26/6			12	7/6/78	
Simcoe	13	17/5	31	11-12/3	11	22/7	8	24/6	31	24/6			31	11-12/3/78	
Kitchener	13	17/5	17	6-7/6	10	15/6	6	25/6	17	25/6			17	6-7/6/78	
St Catharines	13	24/6	10	22/7	1	21/7	5	24/6	13	24/6			13	24/6/77	
Hamilton	4	24/6	8	20/7	8	20/7	7	22/7	8	22/7			8	20/7/78	
Scarborough	3	4/7 15/7	12	27/5	7	21/7 23/7	4	14/6	12	14/6			12	27/5/78	
Stouffville	13	21/5	11	20/6 27/5 11/6	10	21/7	12	24/6	13	24/6			13	21/5/77	
Orono	9	21/5 22/5 31/5	13	20/7	12	17/6	9	23/5	13	23/5			13	20/7/78	
Ottawa	4	28/6	12	11/6	5	17/6	1	25/6	12	25/6			12	11/6/78	
Cornwall	0	-	22	11-12/6	15	15/6	15	24/6	22	24/6			22	11-12/6/78	
Sudbury	7	21/5	12	28-29/5	7	14/6	0	—	12	—			12	28-29/5/78	

Note: Date is given as 21/5 which denotes May 21st, and as 23/6/80 which denotes June 23rd, 1980.

(Table 4) The magnitude month and year of occurrences of the highest and lowest monthly during daily ozone concentration at each site during 1977-80

Highest monthly average month year	Site	Lowest monthly average month year
47.0 May 1977	Huron Park	10.2 Dec 1979
43.4 July 1977	Windsor	4.3 Dec 1978
63.9 July 1979	Merlin	10.6 Dec 1979
42.3 May 1978	Petrolia	8.9 Dec 1979
35.8 July 1977	London	6.5 Dec 1979
53.3 July 1977	Simcoe	14.1 Dec 1977
43.7 July 1978	Kitchener	9.7 Dec 1980
42.0 July 1977	St Catherines	6.7 Nov 1979
30.5 July 1978	Hamilton	6.3 Nov 1979
30.0 July 1978	Scarborough	5.1 Dec 1979
44.3 May 1978	Orono	13.4 Nov 1979
50.0 May 1978	Stouffville	10.0 Nov 1978
38.5 July 1978	Ottawa	7.1 Nov 1979
46.3 July 1978	Cornwall	12.2 Nov 1979
33.2 May 1978	Sudbury	8.0 Nov 1979

(Table 5) Monthly probability of hourly ozone higher than certain concentrations in southwestern and central southern regions of Ontario

	February		March		April		May		June		July		August		September		Year	
concentration	Px10 ⁻²	N	Px10 ⁻²	N	Px10 ⁻²	N	Px10 ⁻²	N	Px10 ⁻²	N	Px10 ⁻²	N	Px10 ⁻²	N	Px10 ⁻²	N	Px10 ⁻²	N
>120 ppb	-	-	5	2.3	0.6	0.2	7.5	2.0	6.8	1.5	17.8	4.0	2.5	0.7	0.2	0.04	3.5	10.74
>82 ppb	0.9	0.2	2.6	6.5	7	2.1	90	25.4	106	26.0	165	41.3	76	20.1	22	5.5	42.0	127.1

Note: P = probability, N = number of hours

(Table 6) Site and magnitude of the highest maximum day-average and maximum one-hour ozone concentration during each month (1977-1980)

Name of site	Maximum day-average (ppb)	Month	Maximum one-hour (ppb)	Name of site
Huron Park	55	January	79	Cornwall
Petrolia	59	February	93	Merlin
Simcoe	116	March	171	Simcoe
Petrolia	78	April	127	Petrolia
Orono	87	May	211	Windsor
Simcoe	93	June	137	Stouffville
Kitchener	97	July	167	Merlin
St Catherines	77	August	148	Petrolia
Kitchener	95	Sept.	129	Petrolia
Cornwall	50	October	77	Ottawa
Simcoe	47	November	74	Kitchiner
Huron Park	55	December	57	Huron Park
Simcoe	116	Year	211	Windsor

(Table 7) Magnitude, Month of Occurrence and Location of the highest Yearly maximum day-average and maximum one-hour ozone concentration during 1977-1980 (arranged in order of magnitude)

Highest Maximum day-average				Maximum one-hour concentration			
Order of Magnitude	Site	concentration	Month	Order of Magnitude	Site	concentration	Month
1	Simcoe	116	March	1	Windsor	211	May
2	Merlin	101	March	2	Orono	181	May
3	Huron Park	98	March	3	Stouffville	172	May
4	Kitchener	97	July	4	Simcoe	171	March
5	Petrolia	91	March	5	Merlin	167	July
6	Cornwall	90	June	6	Scarborough	165	July
7	Windsor	89	July	7	Petrolia	148	May
8	Orono	87	July	8	St Catherines	147	May
9	Sudbury	87	May	9	Huron Park	137	May
10	St Catherines	84	July	10	Kitchener	136	July
11	Stouffville	80	June	11	Ottawa	133	May
12	Ottawa	79	July	12	London	120	May
13	Hamilton	75	July	13	Hamilton	119	July
14	London	71	May	14	Sudbury	118	July
15	Scarborough	64	July	15	Cornwall	116	May

(Table 8) Number of days daylight station episode (DSE) and nighttime station episode (NSE) occurred during (1977-1980) (see text for definition of DSE & NSE)

Year	1977		1978		1979		1980		Totoal 1977-80	
Time of occurrence	DSE	NSE	DSE	NSE	DSE	NSE	DSE	NSE	DSE	NSE
Station										
Huron Park	19	-	22	6	7	-	5	-	53	6
windsor	34	1	27	1	7	-	17	1	85	3
Merlin	36	1	27	2	5	-	5	1	73	4
Sarina	10	1	15	1	17	-	6	1	48	3
Petrolia	22	1	32	1	15	1	4	-	73	3
London	8	-	12	1	4	-	6	1	30	2
Simcoe	22	2	33	7	10	-	5	-	70	9
Kitchener	7	2	20	7	5	1	6	-	38	10
St Catherines	12	4	21	4	1	-	9	1	43	9
Hamilton	0	-	8	3	4	-	2	-	14	3
Scarborough	2	-	14	-	6	-	2	-	24	-
Orono	23	-	35	-	21	-	6	-	85	-
Stouffville	11	-	24	-	15	-	4	-	54	-
Ottawa	2	-	6	3	2	-	0	-	10	3
Cornwall	1		13	3	5	2	4	2	23	8
Sudbury	2	-	4	3	2	1	0	-	8	4

(Table 9) Monthly and yearly frequency of daylight station episode (DSE unbracketed) and nighttime station episode (NSE, bracketed) during (1977-1980) (see text for definition of DSE & NSE)

Month	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Year
Station									
Huron Park		2(2)	1	10	8	18(3)	10	4(1)	53(6)
windsor		1	1	19(2)	15(1)	30	13	6	85(3)
Merlin		2(1)	1	13	13(1)	31(2)	11	2	73(4)
Petrolia		2	1	12(2)	23	18(1)	12	5	73(3)
Sarina		0	1	12(1)	11	13(2)	7	4	48(3)
London		1	1	6	5	14(1)	3(1)	0	30(2)
Simcoe	1	5(2)	3	13(2)	16(2)	20(2)	9(1)	3	70(9)
Kitchener		0	1	7(2)	14(2)	9(5)	5(1)	2	38(10)
St Catherines		0(2)	1	10(1)	9(3)	18(2)	5(1)	0	43(9)
Hamilton		0	0	1	4	6(2)	2(1)	1	14(3)
Scarborough		0	0	5	3	12	4	0	24(0)
Orono		0	3	21	16	26	17	2	85(0)
Stouffville		0	0	15	12	21	5	1	54(0)
Ottawa		0	1	2	6(1)	1(1)	0	0	10(3)
Cornwall		0	0	4(1)	13(6)	5(1)	1	0	23(8)
Sudbury		0	0	2(2)	2(2)	4(1)	0	0	8(4)

(Table 10) Frequency distribution of days daylight station episodes (DSE, unbracketed figures) and nighttime station episodes (NSE, bracketed figures) persisted for 3 hours or more with corresponding average daily means of ozone concentration between 1000-2100 and 2200-0900 EST and the maximum & minimum mean hourly ozone concentration (ppb) of each duration during 1977 - 1980.

Station	Number of hours of persistence											
	3 hours			4 hours			5 hours			6 hours		
	A	B	C	A	B	C	A	B	C	A	B	C
Huron Park	8 (3)	67 (65)	75 (72)	7 (2)	74 (75)	81 (76)	8 (76)	83 (82)	71 (70)	7 (77)	84 (84)	71 (70)
Windsor	16 (2)	65 (52)	79 (63)	13 (68)	78 (78)	56 (41)	10 (75)	88 (61)	64 (61)	16 (79)	85 (72)	8 (72)
Merlin	10 (70)	74 (59)	74 (59)	9 (71)	78 (60)	60 (63)	13 (77)	82 (80)	73 (73)	10 (81)	93 (73)	12 (86)
Petrolia	13 (65)	72 (56)	72 (56)	11 (71)	79 (64)	64 (58)	3 (70)	70 (67)	67 (67)	4 (82)	92 (85)	5 (83)
Sarnia	4 (74)	77 (61)	68 (61)	4 (73)	77 (60)	67 (60)	10 (74)	81 (69)	69 (69)	3 (80)	89 (73)	2 (82)
London	7 (69)	75 (66)	66 (61)	9 (72)	75 (63)	69 (63)	8 (79)	85 (74)	74 (65)	8 (79)	81 (69)	14 (84)
Simcoe	5 (70)	77 (60)	60 (63)	4 (70)	76 (63)	63 (63)	4 (74)	76 (70)	70 (68)	4 (81)	85 (78)	7 (85)
Kitchener	11 (66)	76 (59)	59 (53)	9 (74)	80 (69)	69 (63)	9 (75)	81 (68)	68 (60)	2 (82)	83 (80)	7 (83)
St Catharines	3 (66)	75 (53)	53 (53)	4 (73)	77 (67)	67 (63)	4 (79)	79 (78)	78 (68)	3 (81)	83 (79)	7 (85)
Hamilton	8 (59)	71 (53)	53 (53)	5 (65)	73 (63)	57 (63)	3 (74)	81 (66)	66 (66)	2 (75)	78 (73)	3 (84)
Scarborough	15 (69)	75 (60)	60 (62)	13 (72)	80 (72)	62 (62)	8 (72)	76 (65)	65 (65)	7 (78)	86 (74)	15 (85)
Orono	14 (69)	73 (61)	61 (61)	11 (76)	81 (68)	68 (68)	5 (80)	85 (75)	75 (75)	8 (85)	91 (77)	4 (82)
Stouffville	2 (76)	77 (75)	75 (75)	3 (74)	76 (72)	72 (72)	3 (78)	80 (77)	77 (77)	1 (81)	81 (78)	1 (81)
Ottawa	4 (69)	73 (67)	67 (67)	2 (80)	81 (79)	79 (79)	4 (78)	82 (73)	73 (73)	1 (84)	84 (84)	1 (87)
Cornwall	1 (75)	75 (66)	66 (66)	1 (82)	82 (82)	82 (82)	3 (82)	84 (80)	80 (80)	1 (91)	91 (89)	1 (89)
Sudbury	1 (71)	71 (71)	71 (71)	1 (63)	63 (63)	63 (63)	2 (72)	78 (78)	78 (78)	1 (81)	81 (81)	1 (81)

A = No. of days, B = average daily means, C = maximum daily means, D = minimum daily means.

(Table 11) Number of days daylight station episodes persisted during 1977 - 1980

[illegible]

(Table 12) Peak ozone concentration and the number of days certain hourly ozone concentrations (ppb) exceeded for at least one day during daylight station episodes (DSE unbracketed figures) and during nighttime station episodes (NSE bracketed figures) in 1977-80

[illegible]

(Table 13) Total (unbracketed figures) and cumulative (bracketed figures) number of daylight (1000 -2100 EST) station episodes occurring at specified number of monitoring stations

Number of days cumulative	Number of Stations															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
in 1977	13 (56)	9 (43)	10 (34)	5 (24)	8 (19)	3 (11)	2 (8)	1 (6)	3 (5)	0 (2)	1 (2)	1 (1)				
in 1978	15 (64)	9 (49)	7 (40)	7 (33)	5 (26)	4 (21)	6 (17)	1 (11)	3 (10)	0 (7)	3 (7)	1 (4)	1 (3)	1 (2)	1 (1)	0 (0)
in 1979	10 (38)	12 (28)	5 (16)	3 (11)	0 (8)	2 (8)	1 (6)	0 (5)	2 (5)	2 (3)	1 (1)					
in 1980	18 (36)	6 (18)	2 (12)	3 (10)	3 (7)	2 (4)	1 (2)	1 (1)								
Total	56	36	24	18	16	11	16	3	8	2	5	2	1	1	1	
Annual average	14.0	9.0	6.0	4.5	4.0	2.25	2.50	0.75	2.00	0.50	1.25	0.50	0.25	0.25	0.25	
Cumulative annual average	48.0	34.0	25.0	19.0	14.5	10.5	8.25	5.75	5.00	3.0	2.50	1.25	0.75	0.50	0.25	

(Table 14) Frequency of the number of hours that surface winds at various speeds were associated with ozone concentrations above 82 ppb, 120 ppb, 153 ppb, between 1200-2100 EST from 1977 to 1980 at Windsor, Simcoe and St. Catharines.

Site	wind direction	Windsor										average wind speed of all occasions	
		NW, N, NE, E					SE, S, SW, W					average wind speed	average speed of all occasions
		0-10	11-20	21-30	31-40	>40	1-10	11-20	21-30	31-40	>40		
	wind speed km/hr	3	-	-	-	-	2	7	-	-	-	12.8	10.8
	ozone level >153 ppb	5	3	-	-	-	5	30	1	-	-	14.0	13.0
	"												
	"	52	39	2	-	-	51	307	119	11	-	16.8	15.7
	"												
		Simcoe											
	ozone level >153 ppb	-	-	-	-	-	-	6	-	-	-	15.0	15.0
	"	1	3	-	-	-	1	10	-	-	-	14.1	13.7
	"	11	21	6	-	-	56	231	170	32	2	18.8	18.6
	"												
		St Catharines											
	ozone level >153 ppb	-	-	-	-	-	-	-	-	-	-	-	-
	"	1	11	-	-	-	1	2	-	2	-	21.0	16.2
	"	32	43	-	-	-	13	71	92	22	3	21.6	18.2
	"												

(Table 15) Annual number of hours of the Association of Ozone Concentrations Higher Than 82 ppb and 120 ppb with Various Wind Directions during 1200 - 2100 EST for 1977-1980 at St. Catharines, Ontario

Concentration	Surface Wind Directions								Total	Ratio of NW,N NE,E to Total	Ratio of SE,W SW,W to Total
	NW	N	NE	E	SE	S	SW	W			
>82 ppb	28	31	9	7	1	53	125	22	276	0.27	0.73
>120 ppb	2	4	3	3	1	1	2	1	17	0.71	0.29

Table (16-a&b) Monthly and Annual number of days & occasions favourable meteorological conditions for elevation ozone concentrations prevailed

(a) Annual Stagnant and non-stagnant conditions

Year	Stagnant conditions							non-stagnant conditions days	Total stagnant & non-stagnant days	Ratio warm to total	Ratio all stagnant to total	Ratio non-stagnant To total
	Warm anti cyclone		total duration days	Highest peak ppb (1)	Lowest peak ppb (1)	Migratory highs day	all stagnant days					
	number of cases	duration days										
1977	2	6+3	9	137	65	22	31	30	61	0.15	0.51	0.49
1978	4	5+5+3+3	16	130	71	28	44	26	70	0.23	0.63	0.37
1979	2	5+4	9	121	75	20	29	21	50	0.18	0.58	0.42
1980	2	3+3	6	81	52	16	22	17	39	0.15	0.56	0.44
1977-80	10	-	38	-	-	88	126	94	220	-	-	0.45
annual average	2.5	-	9.5	137	52	22.0	31.5	23.5	55.0	0.18		

(b) Monthly all favourable conditions (days)

Year	Feb	Mar	Apr	May	June	July	Aug	Sept	Year
1977	-	4	6	13	10	14	10	4	61
1978	1	6	1	14	12	16	14	6	70
1979	-	3	3	7	12	13	5	7	50
1980	-	1	2	5	10	9	8	4	39
1977-80	1	14	12	39	44	52	37	21	220
annual average	0.25	3.5	3.0	9.75	11.0	13.0	9.25	5.25	55.0

(1) Average daily hourly peak ozone concentration (ppb) for the six rural stations

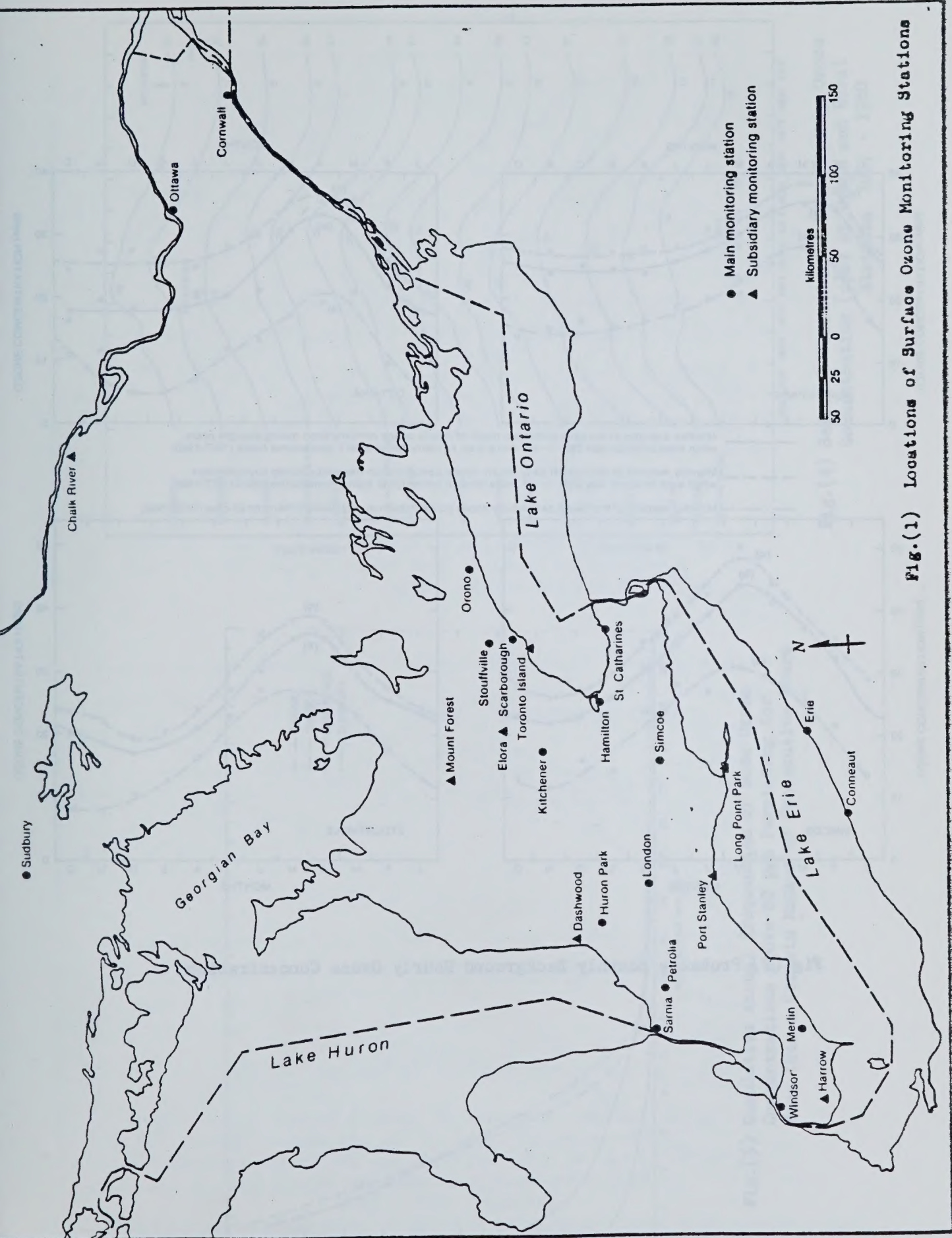


Fig.(1) Locations of Surface Ozone Monitoring Stations

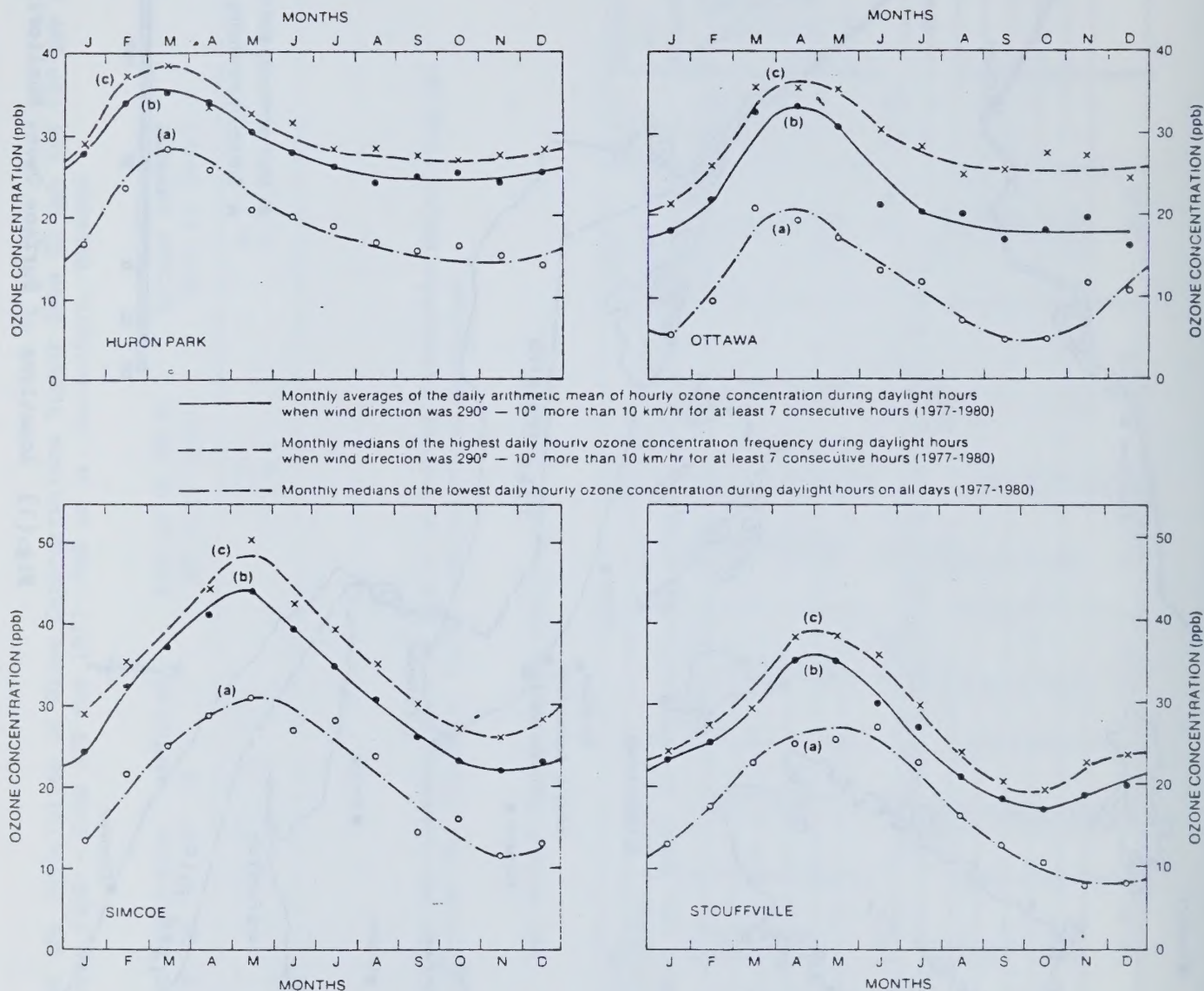


Fig.(2) Probable Monthly Background Hourly Ozone Concentration

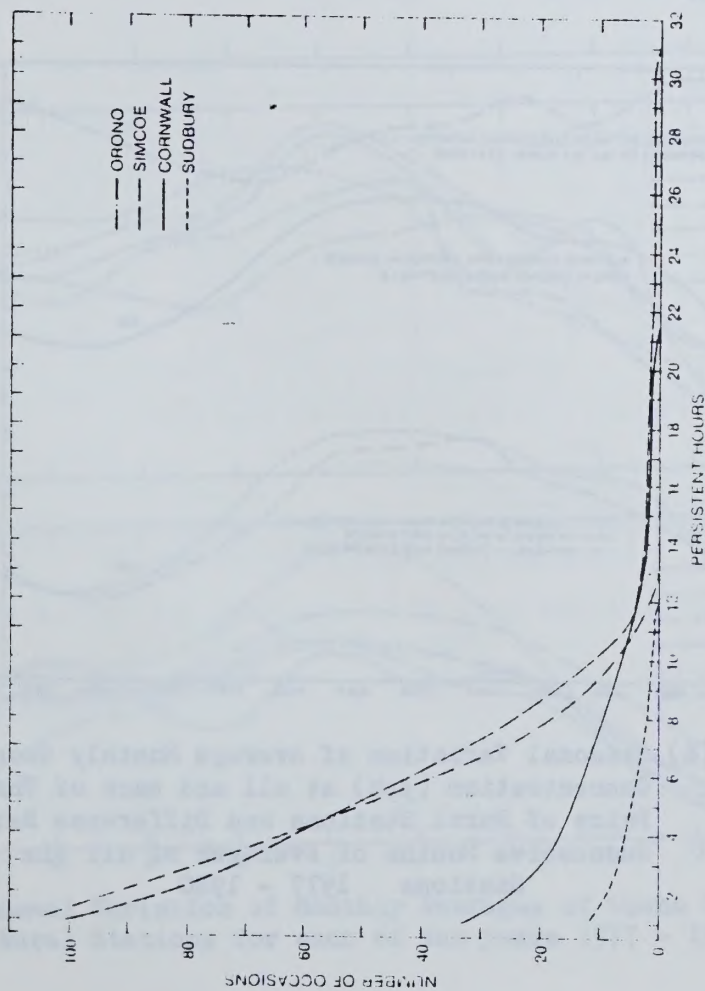


Fig.(3) Cumulative Annual Frequencies of Some Ozone Concentrations above 82 ppb Persisting for More than a Certain Number of Consecutive Hours

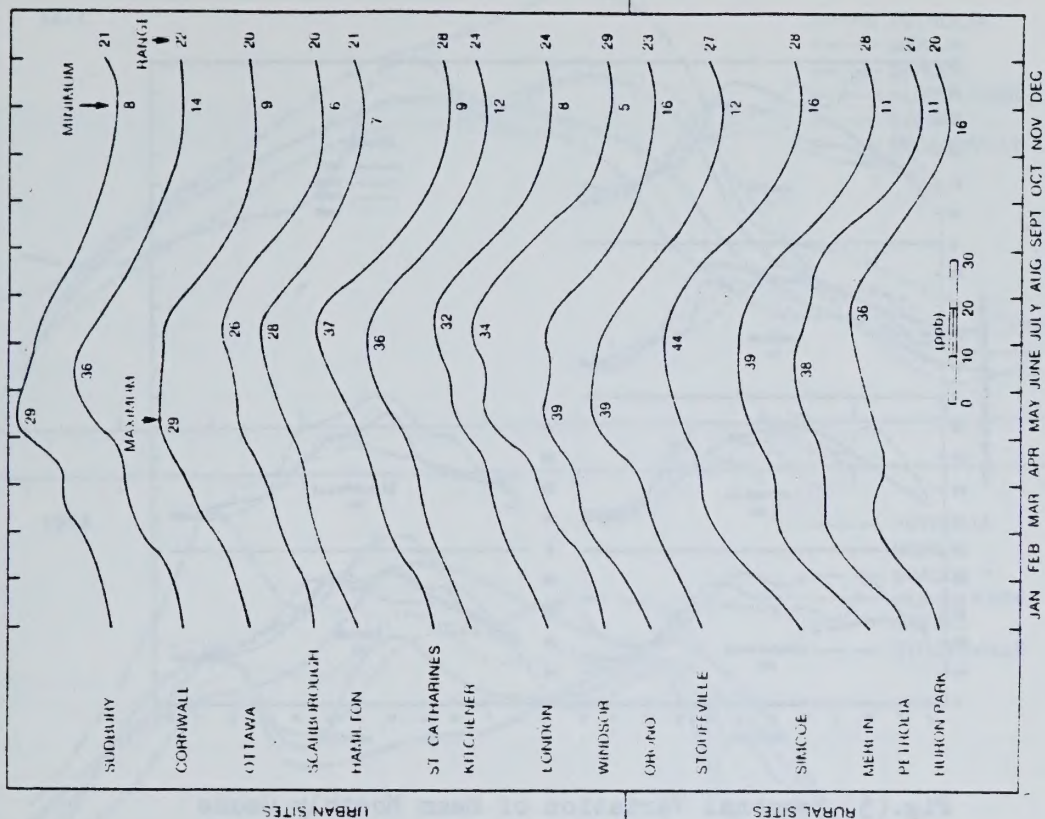


Fig.(4) Seasonal Variation of Mean Monthly Ozone Concentration (ppb) at Urban and Rural Stations 1977 - 1980

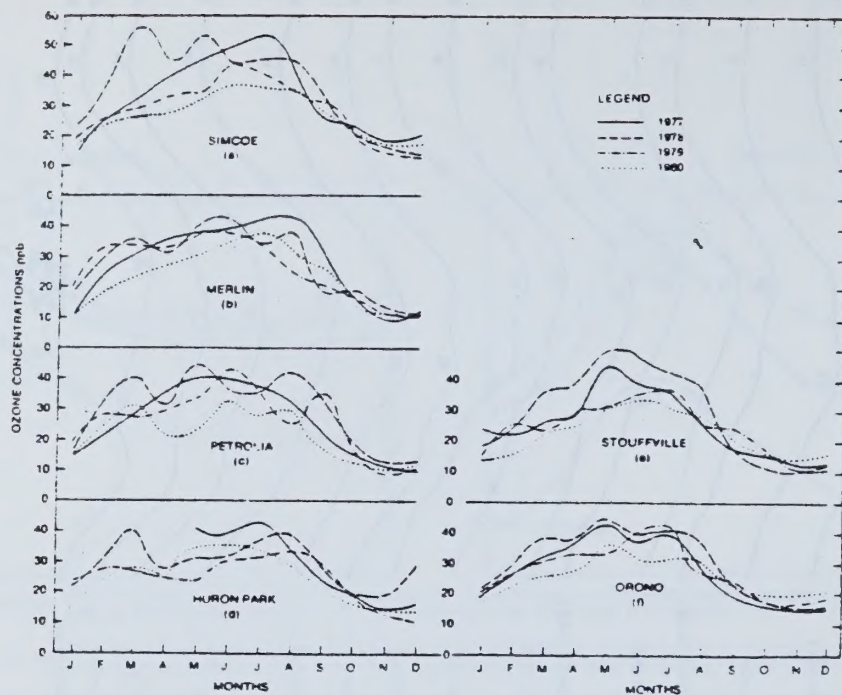


Fig.(5) Seasonal Variation of Mean Monthly Ozone Concentration (ppb) at Each Rural Station for each of the years 1977 - 1980 .

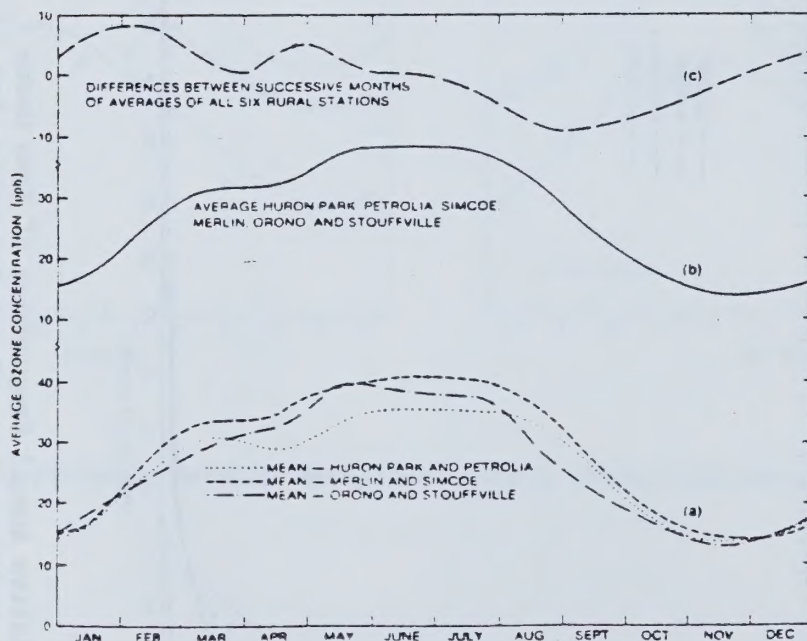


Fig.(6) Seasonal Variation of Average Monthly Ozone Concentration (ppb) at all and each of Three Pairs of Rural Stations and Difference Between Successive Months of Averages of all Six Stations 1977 - 1980

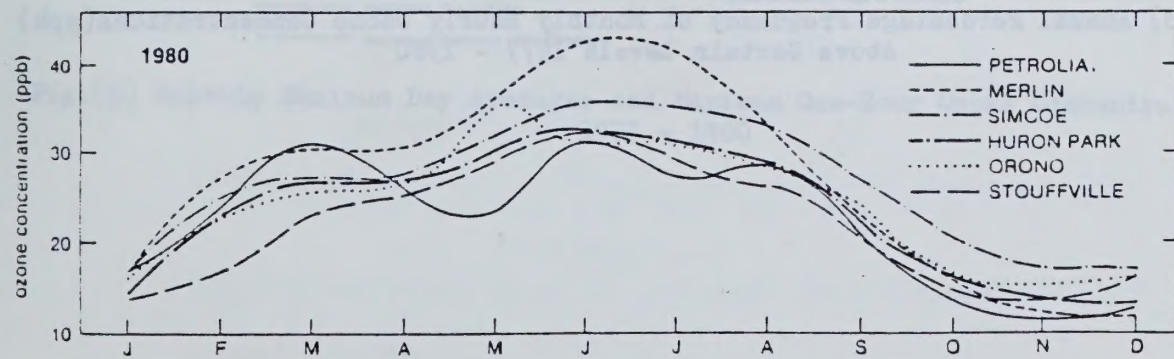
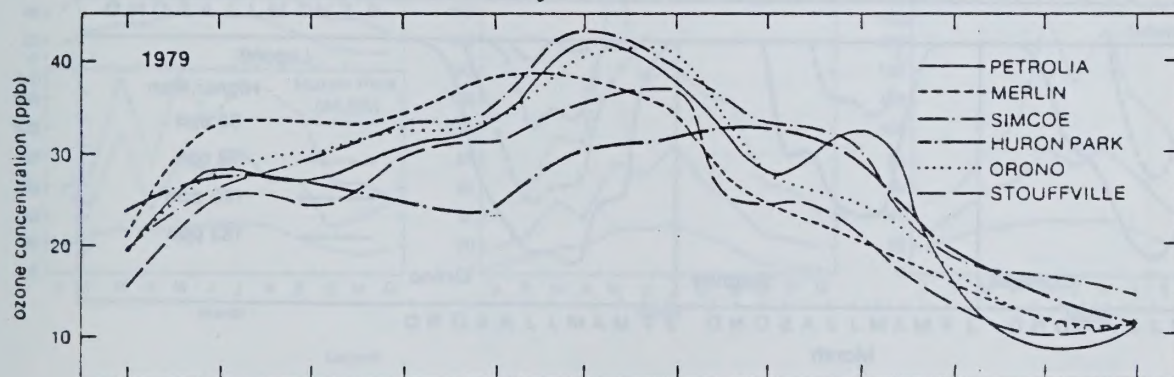
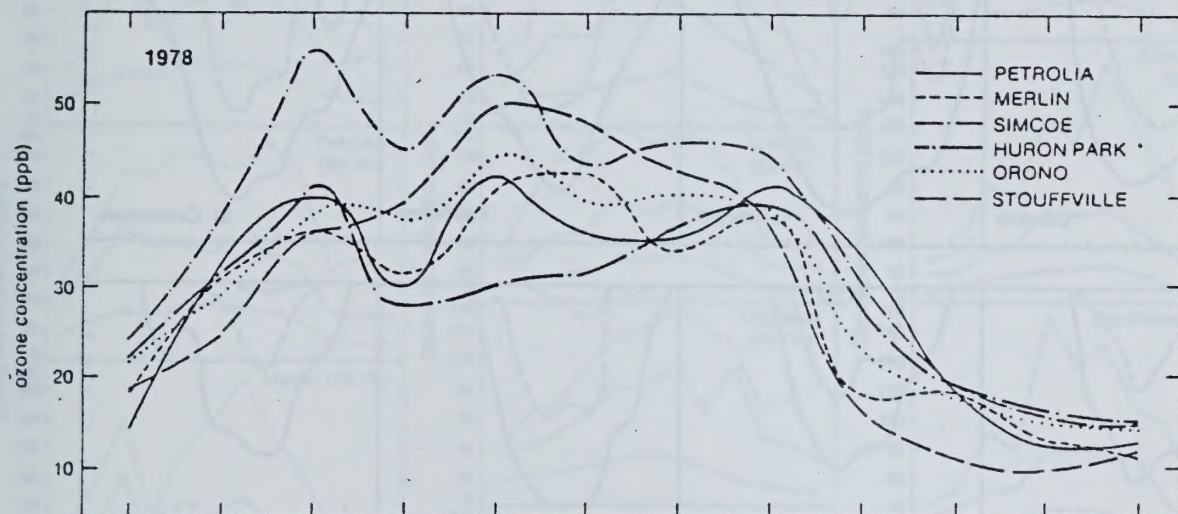
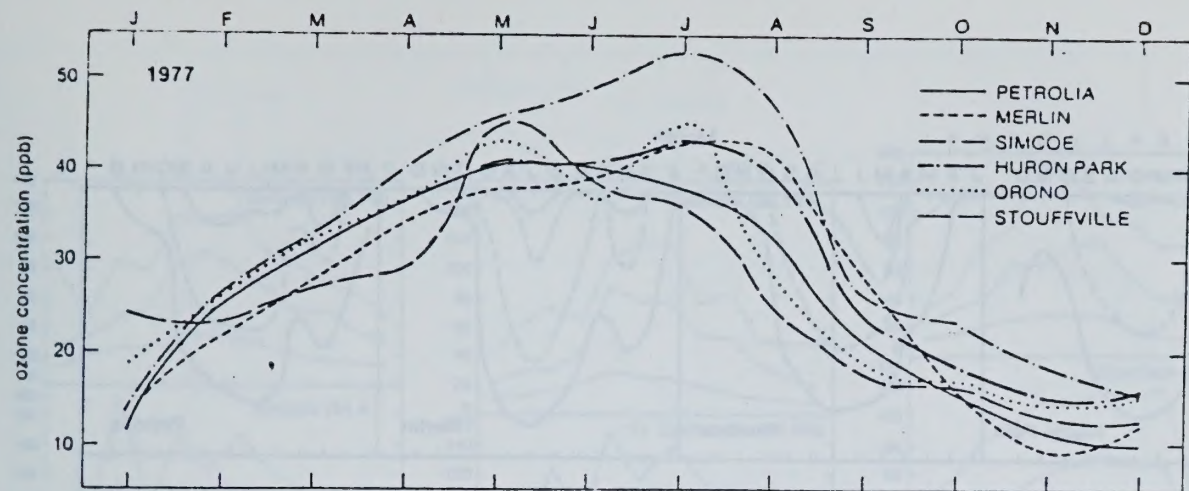


Fig.(7) Seasonal Variation of Monthly Averages of Ozone Concentration(ppb) at Rural Stations for each of the years 1977 - 1980

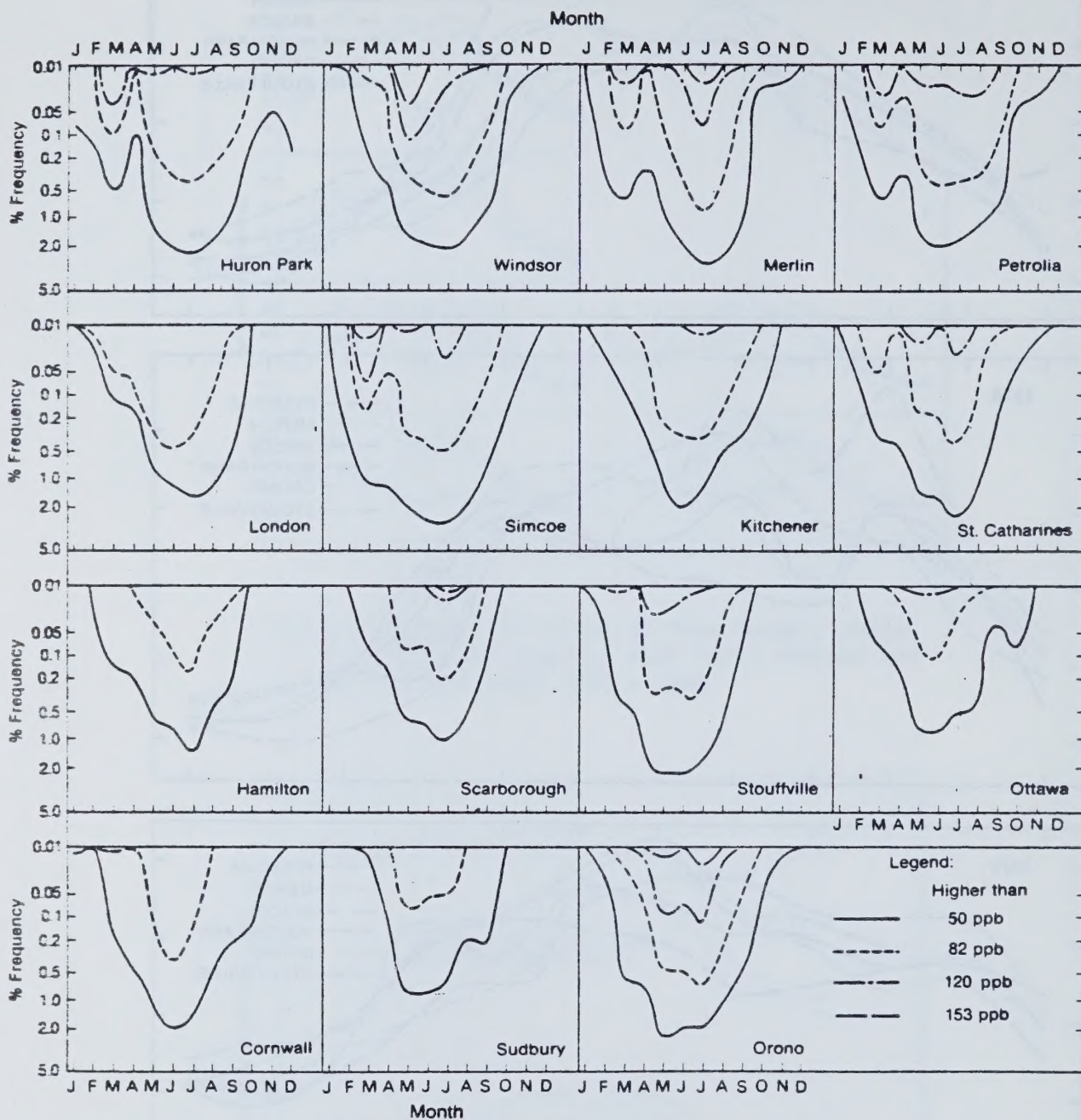


Fig.(8) Annual Percentage Frequency of Monthly Hourly Ozone Concentrations(ppb)
Above Certain Levels 1977 - 1980

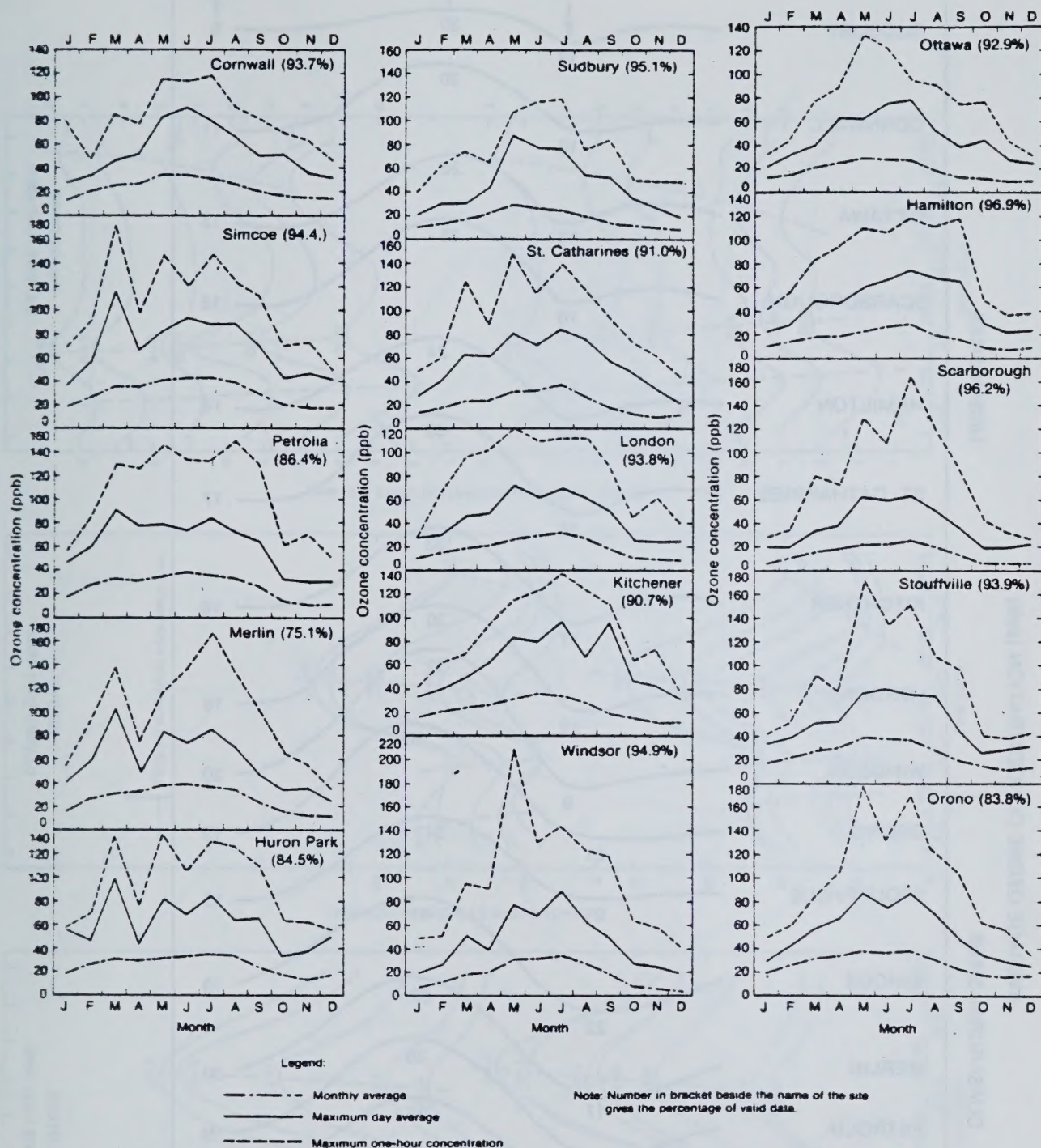


Fig.(9) Monthly Maximum Day Averages and Maximum One-Hour Ozone Concentrations(ppb)
1977 - 1980

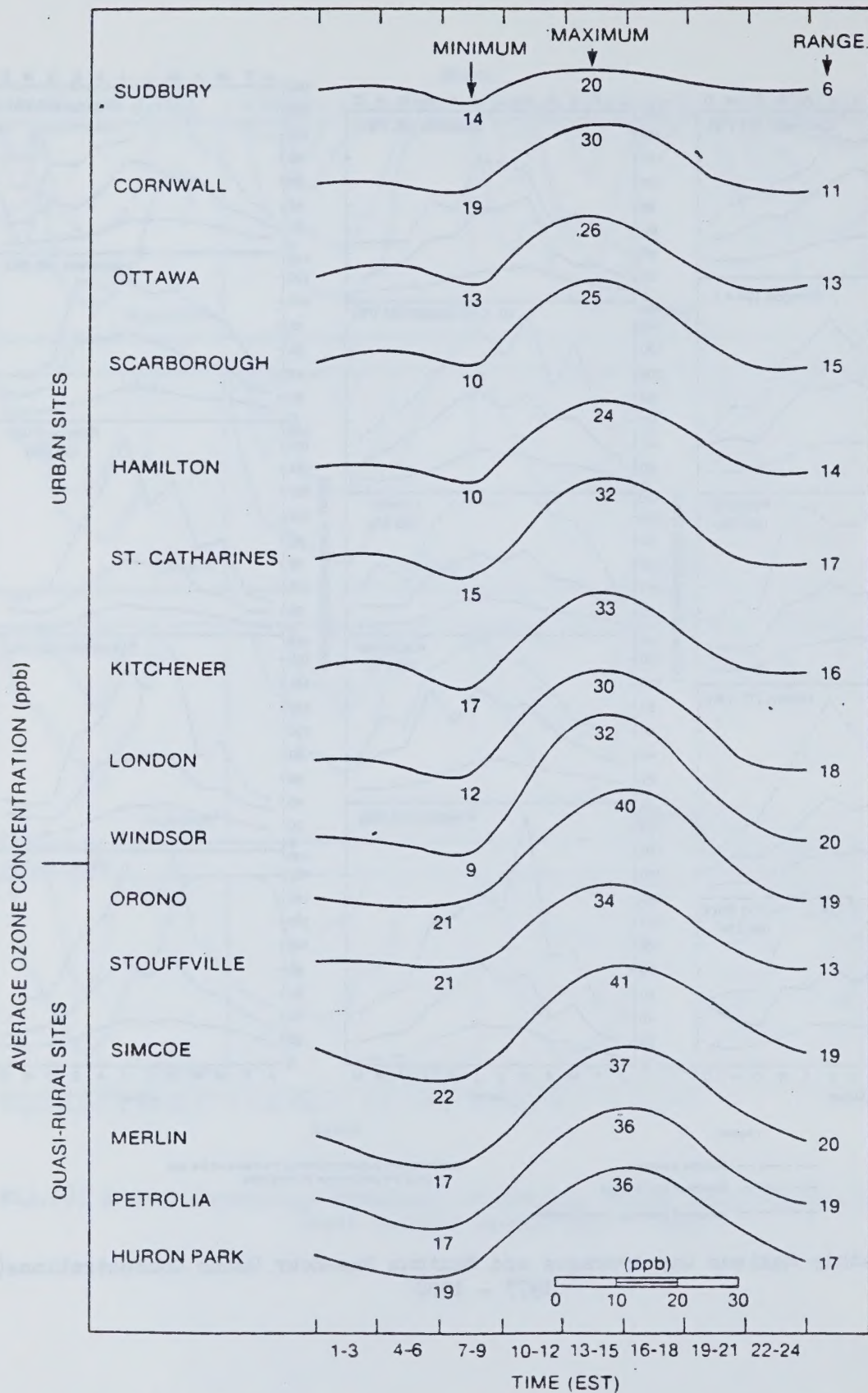


Fig.(10) Yearly Diurnal Variation of Ozone Concentration(ppb)

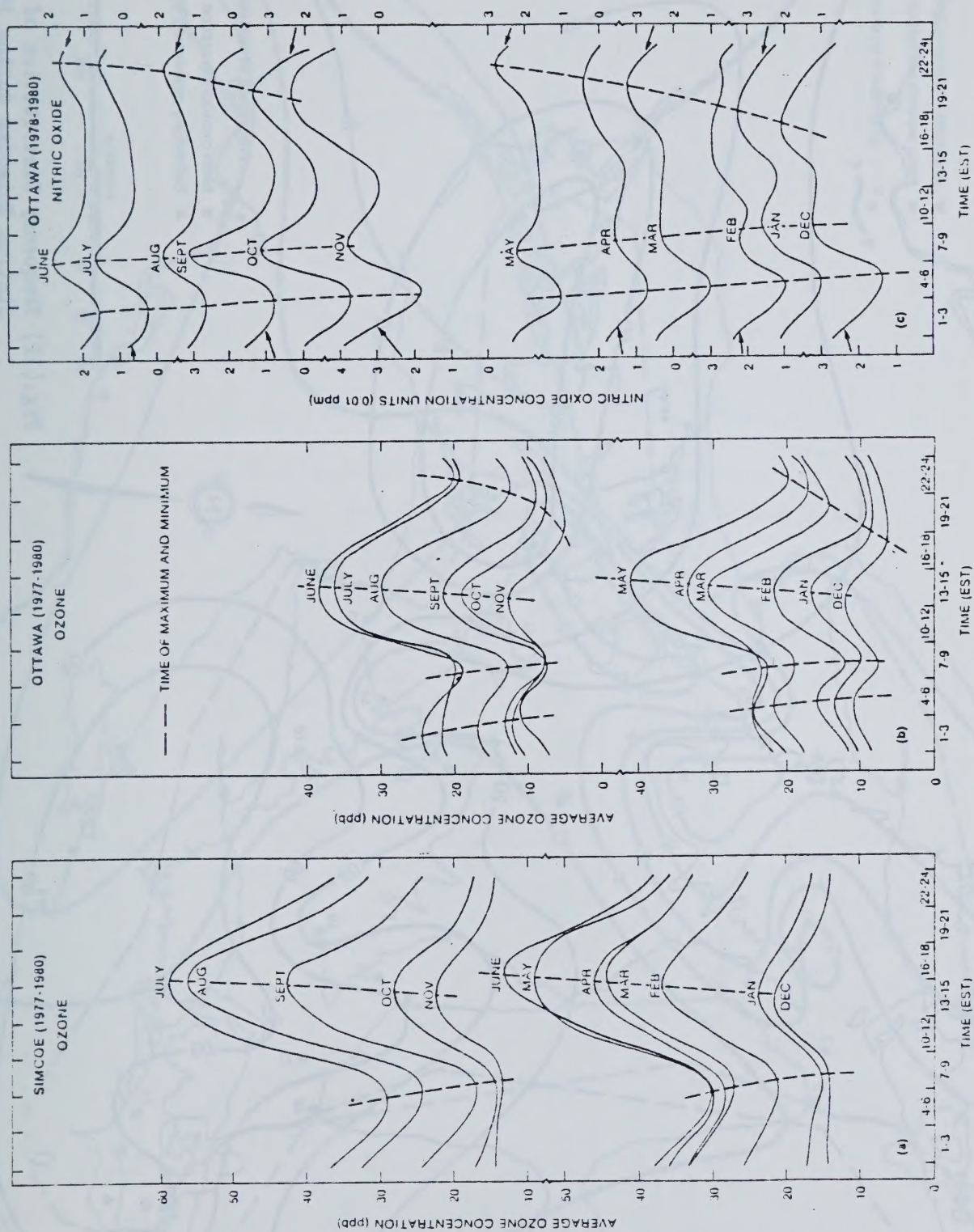


Fig. (11) Yearly Diurnal Variation of Ozone and Nitric Oxide Concentrations

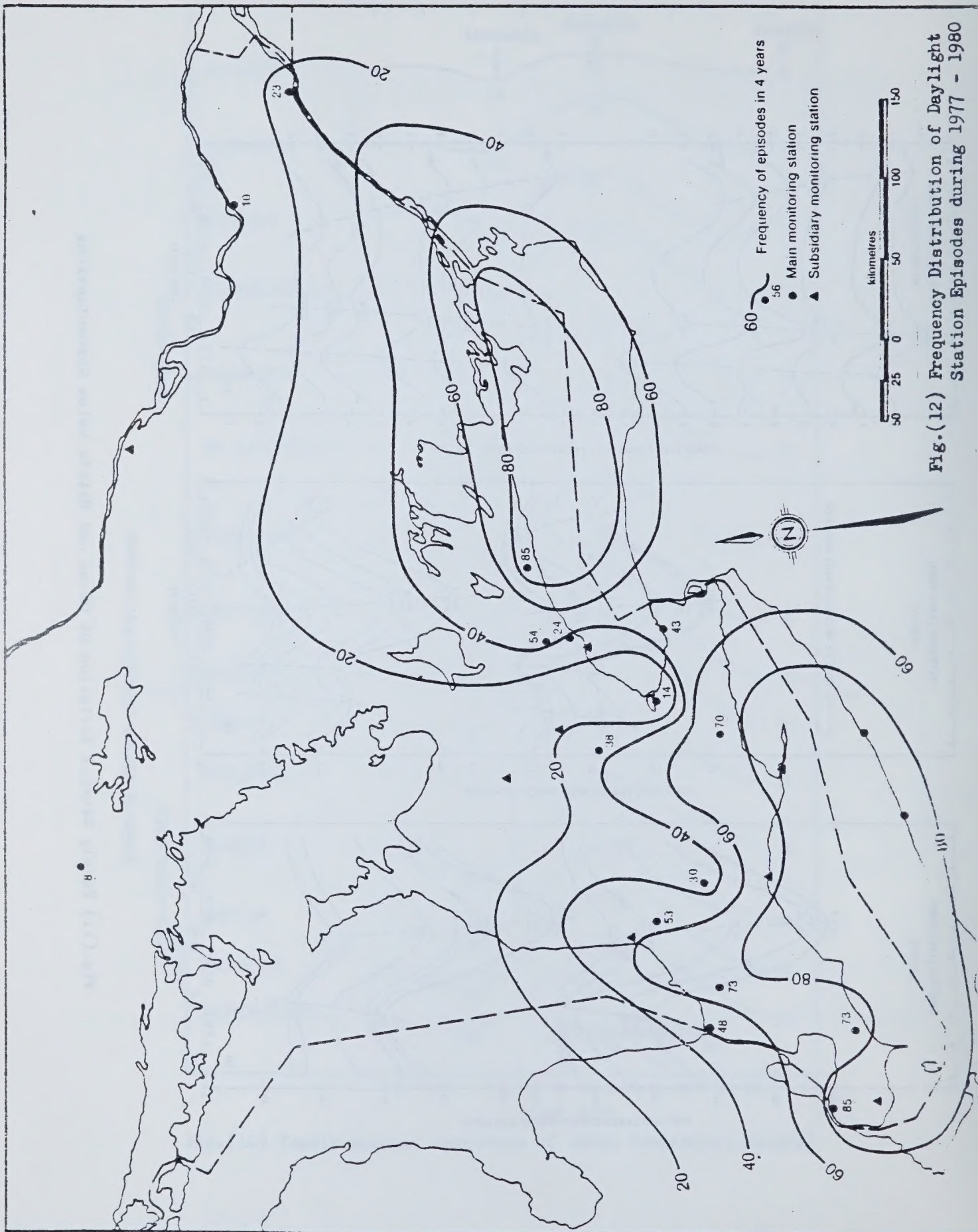


Fig.(12) Frequency Distribution of Daylight
Station Episodes during 1977 - 1980

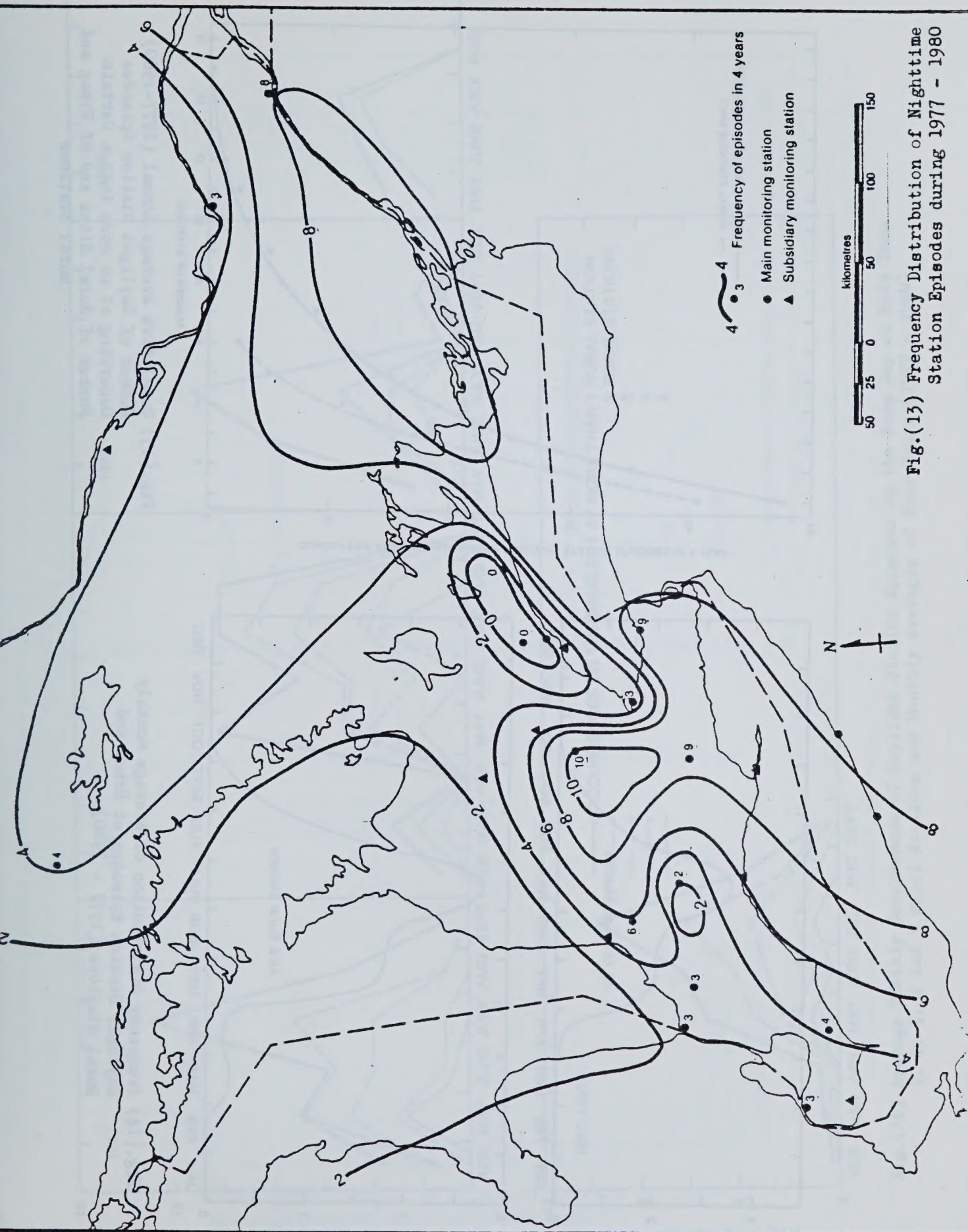


Fig.(13) Frequency Distribution of Nighttime Station Episodes during 1977 - 1980

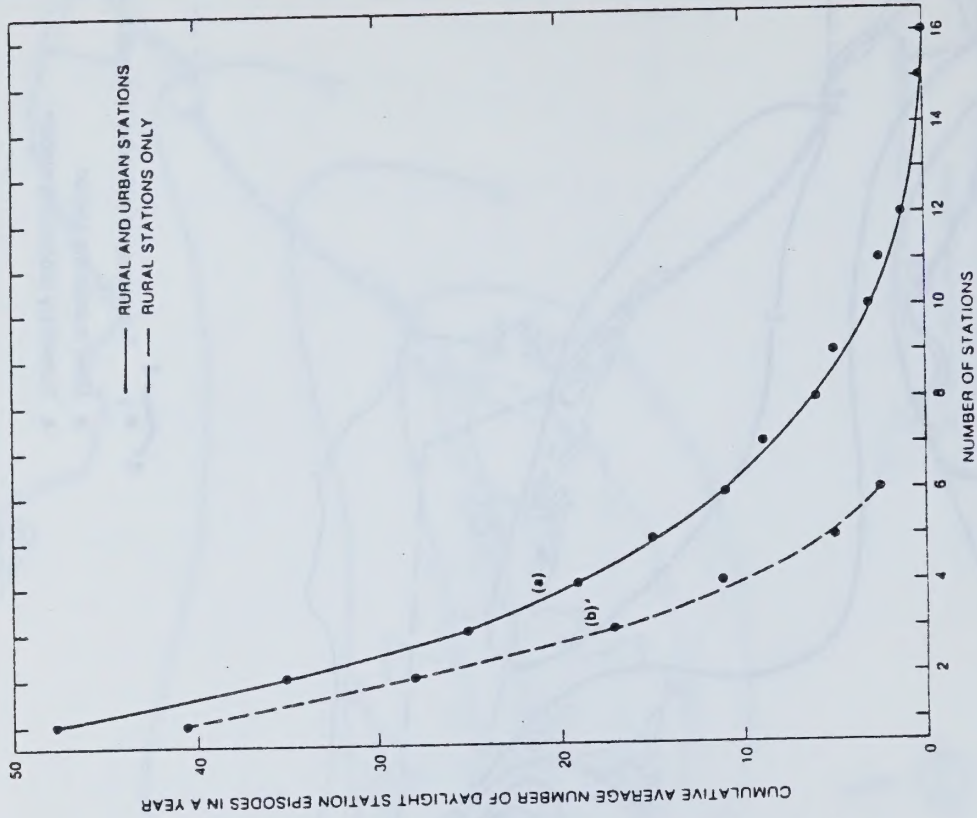


Fig.(15) Cumulative Average Annual (1977-1980)
Number of Daylight Station Episodes
Occurring at no more than a Certain
Number of Rural Sites and of Urban and
Rural Stations

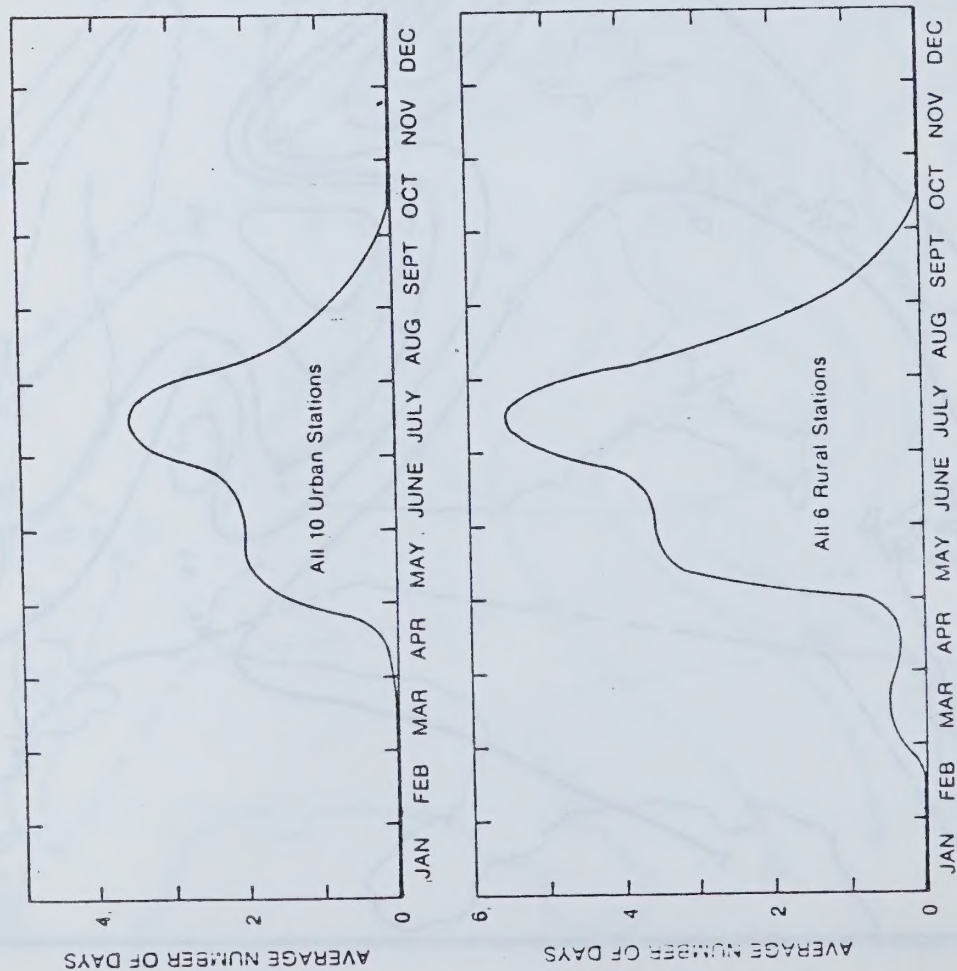


Fig.(14) Frequency Distribution of Average Monthly
Daylight Station Episodes at Urban and
Rural Stations (1977 - 1980)

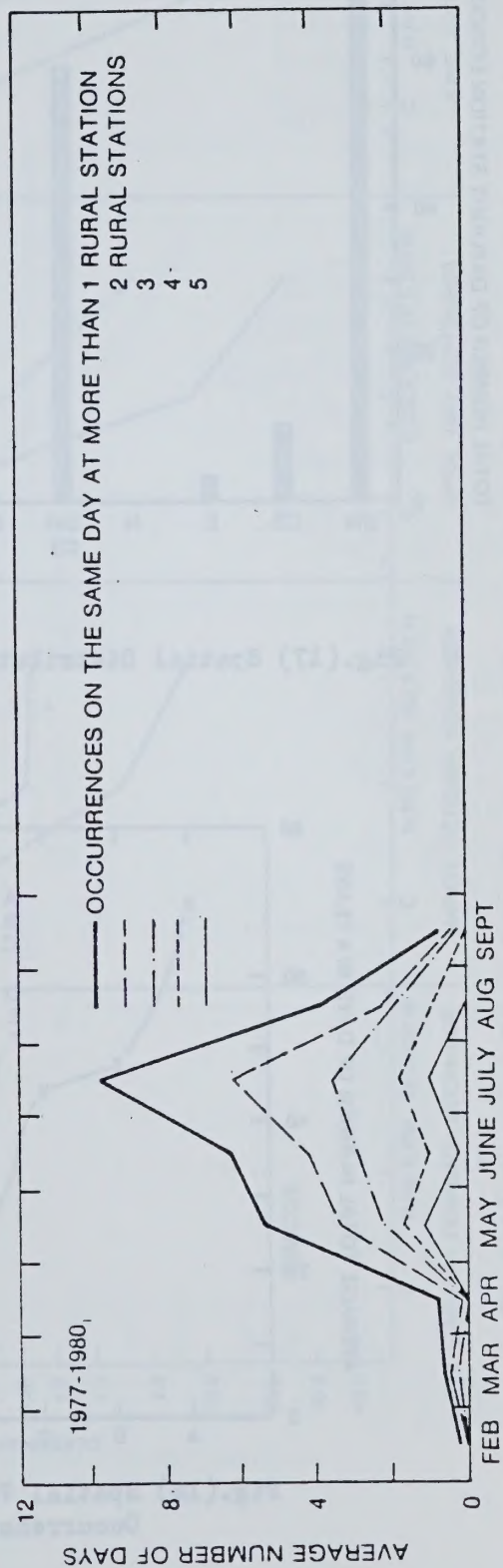
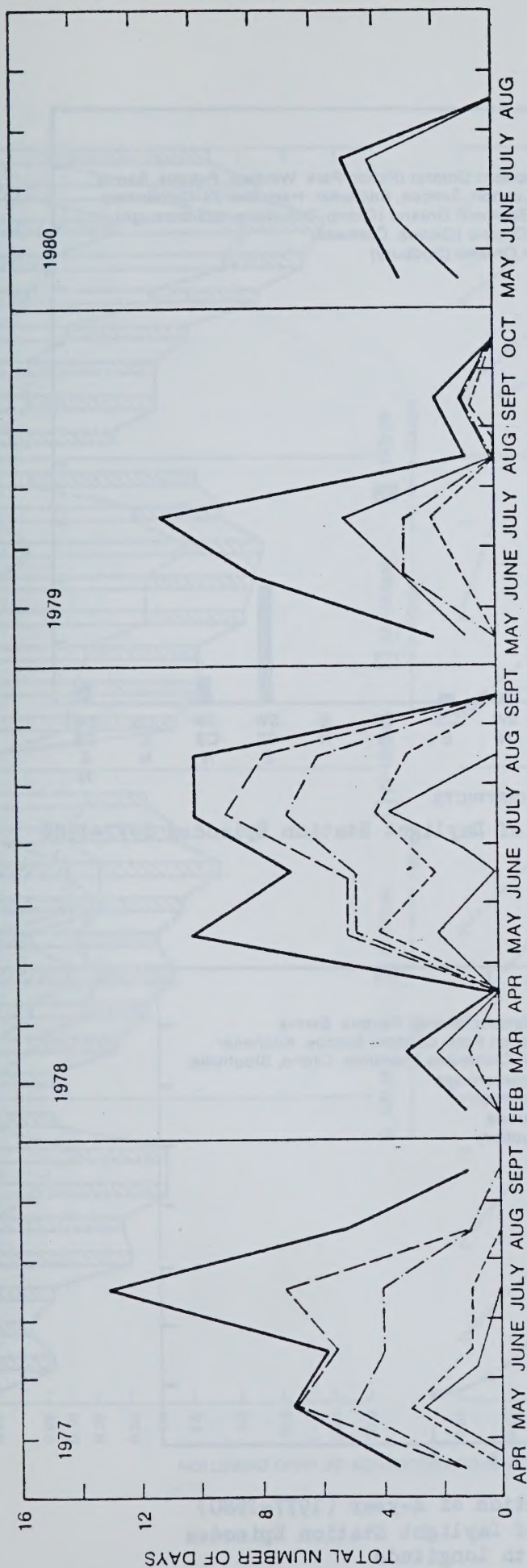


Fig.(16) Average Monthly Occurrences of Daylight Station Episodes on the Same Day at More Than 1, 2, 3, 4 and 5 Rural Stations and Monthly Averages of Four Years (1977 - 1980)

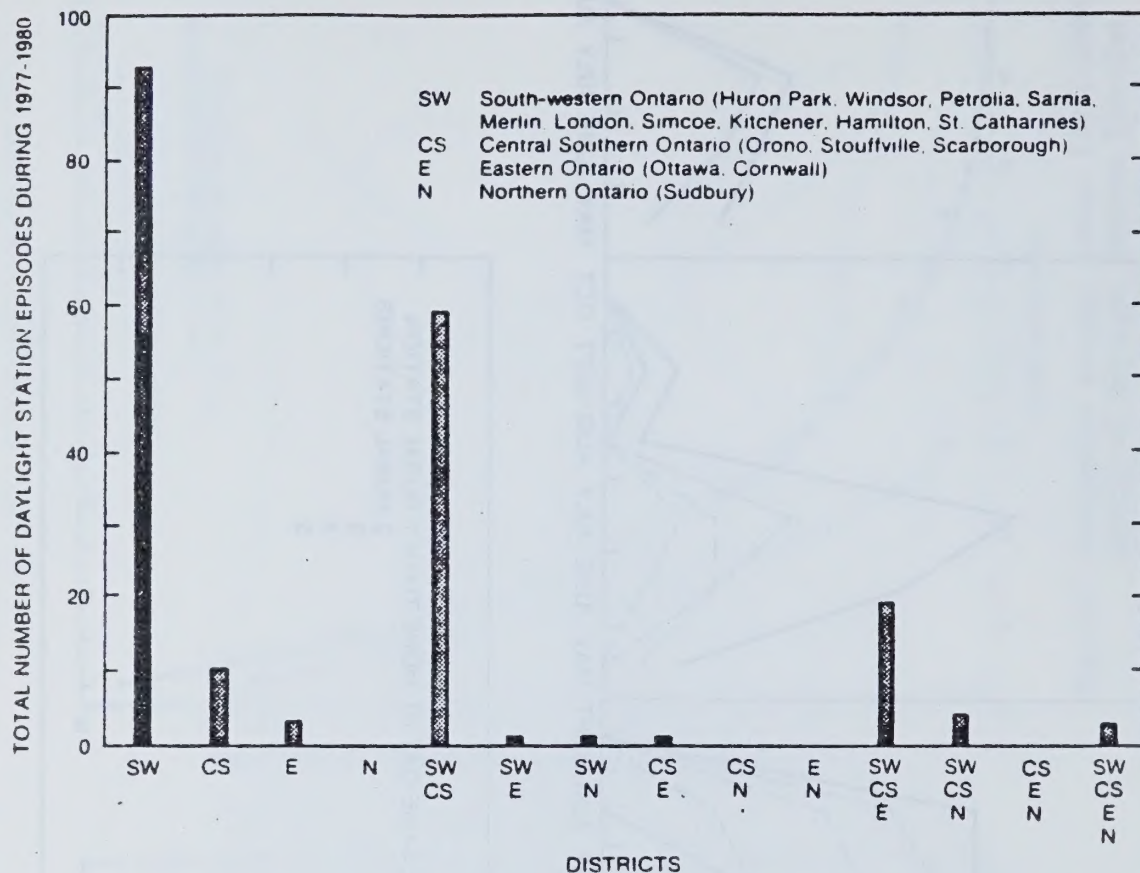


Fig.(17) Spatial Distribution of Daylight Station Episodes 1977-1980

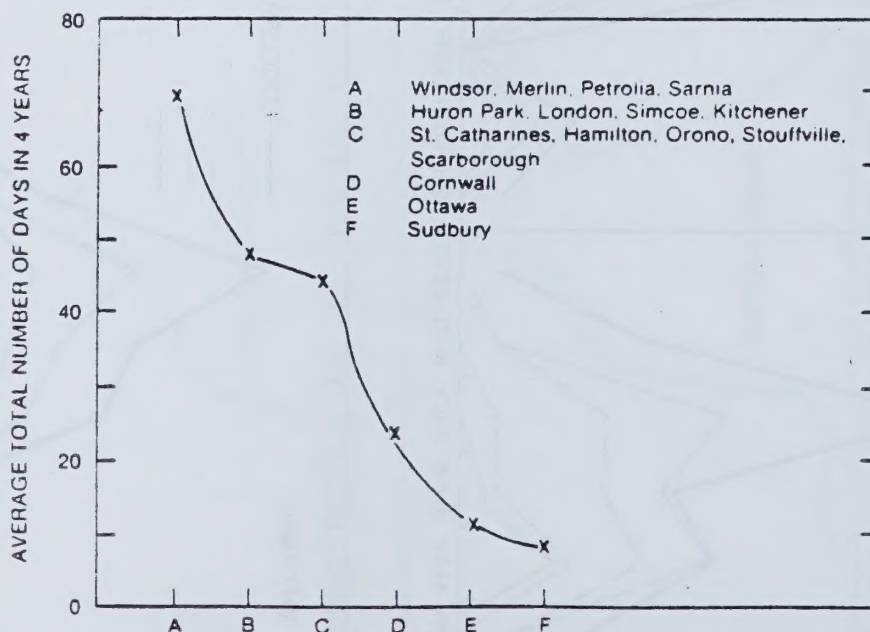


Fig.(18) Spatial Variation of 4-year (1977-1980) Occurrences of Daylight Station Episodes With Longitude

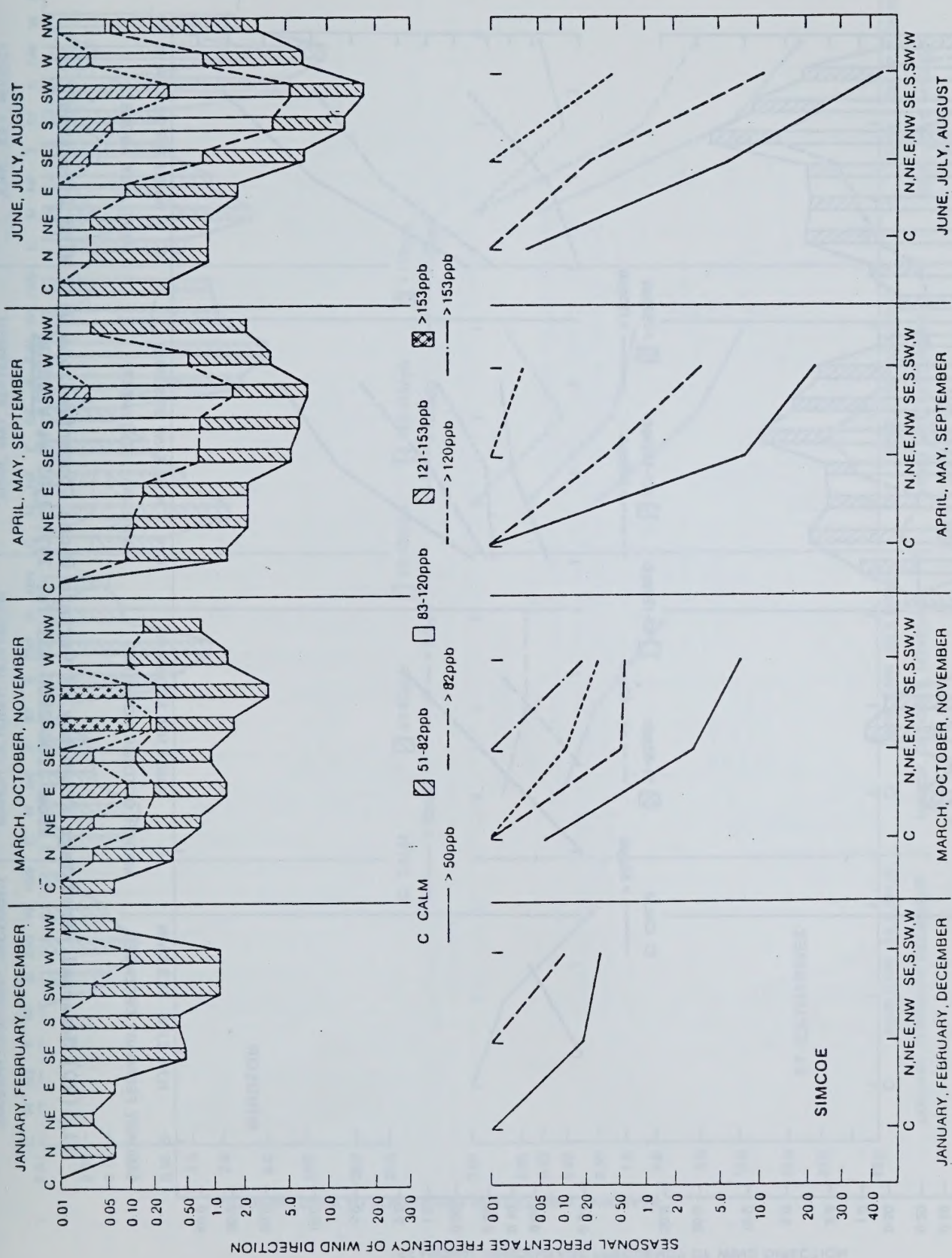


Fig.(19) Seasonal Percentage Frequency of Certain Ozone Concentrations With Wind Direction
From 1200-2100 EST for 1977-1980 at SIMCOE

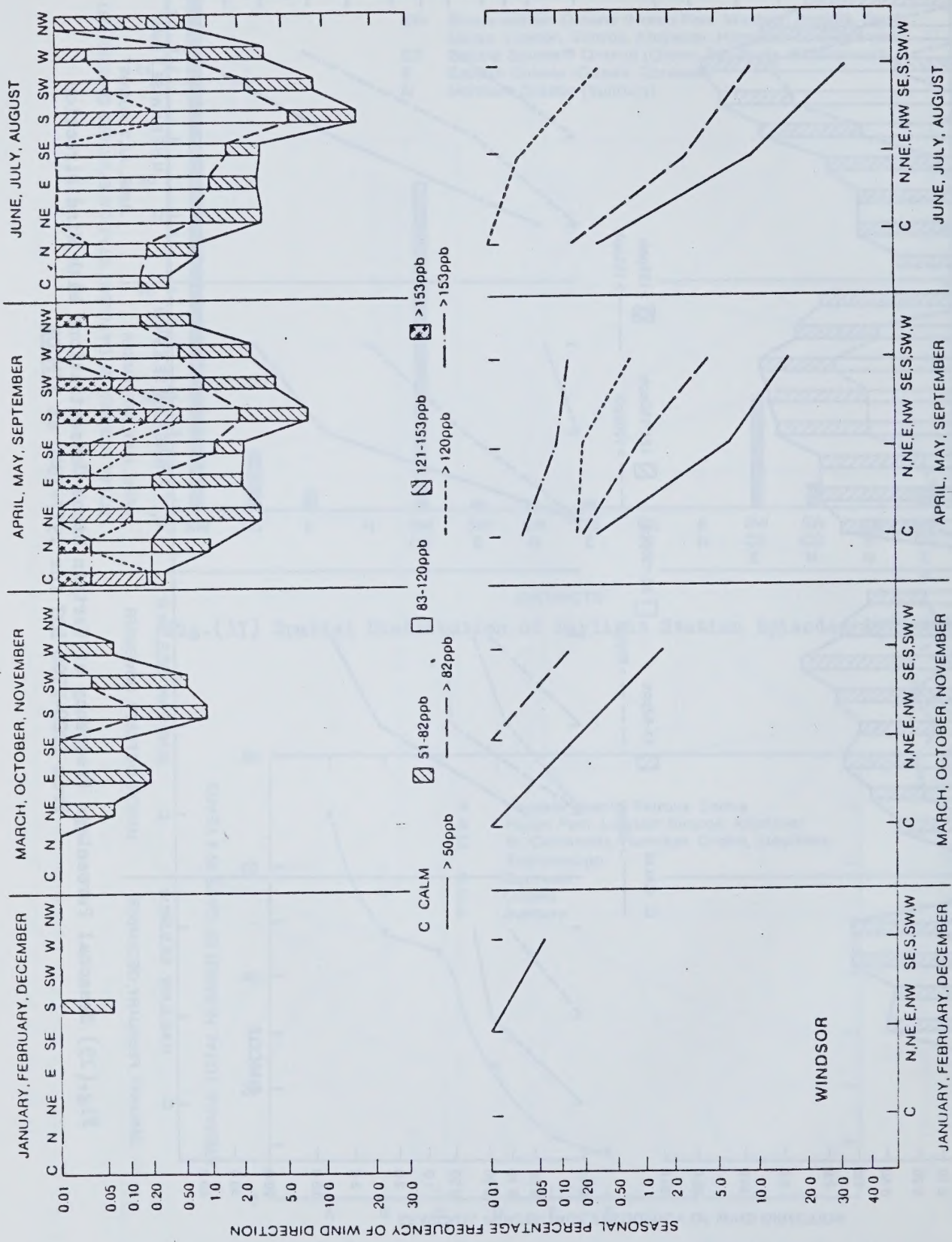


Fig.(20) Seasonal Percentage Frequency of Certain Ozone Concentrations with Wind Direction
From 1200-2100 EST for 1977-1980 at WINDSOR

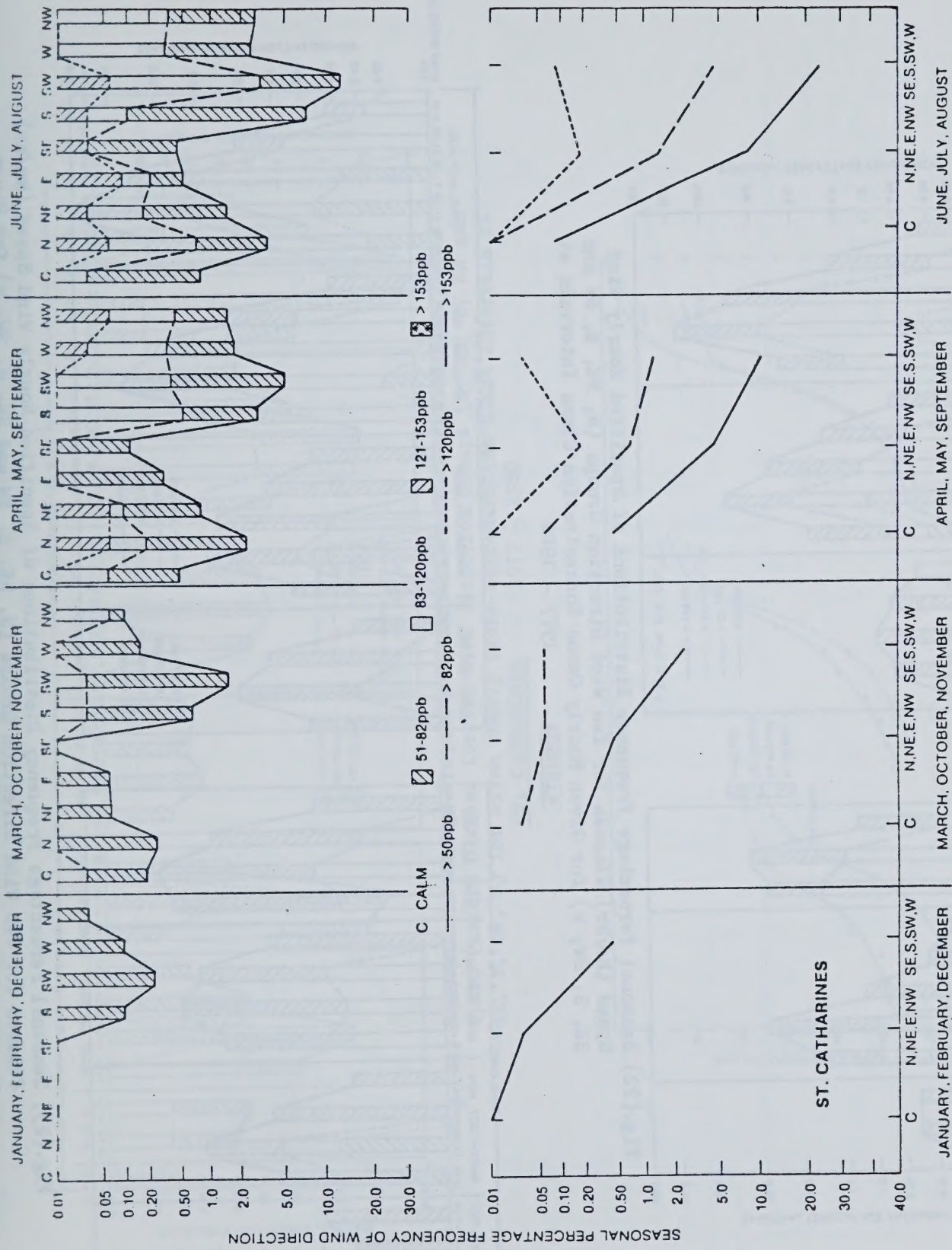


Fig.(21) Seasonal Percentage Frequency of Certain Ozone Concentrations with Wind Direction
From 1200-2100 EST for 1977-1980 at ST. CATHARINES

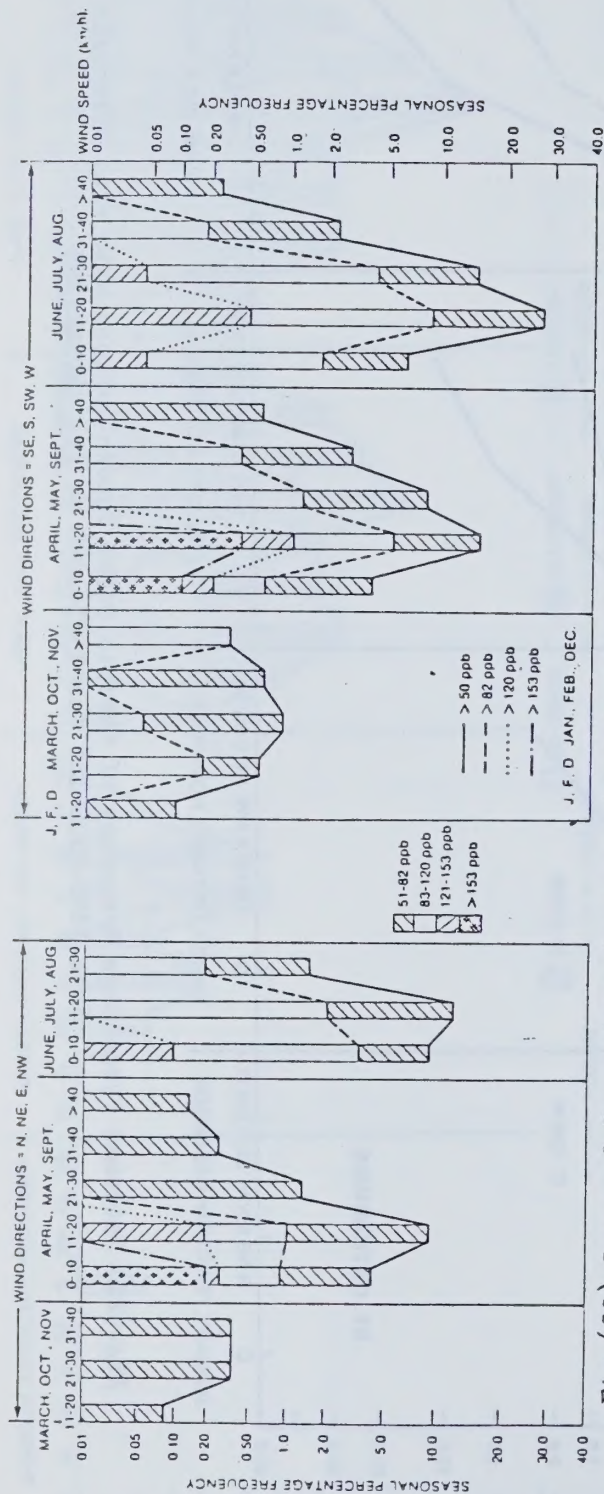


Fig.(22) Seasonal Percentage Frequency Distributions of Specified Hourly Wind Speed (km/hr) Classes for Two Wind Direction Groups (N, NE, E, NW and SE, S, SW, W) for Given Hourly Ozone Concentration Class Intervals at WINDSOR 1977 - 1980

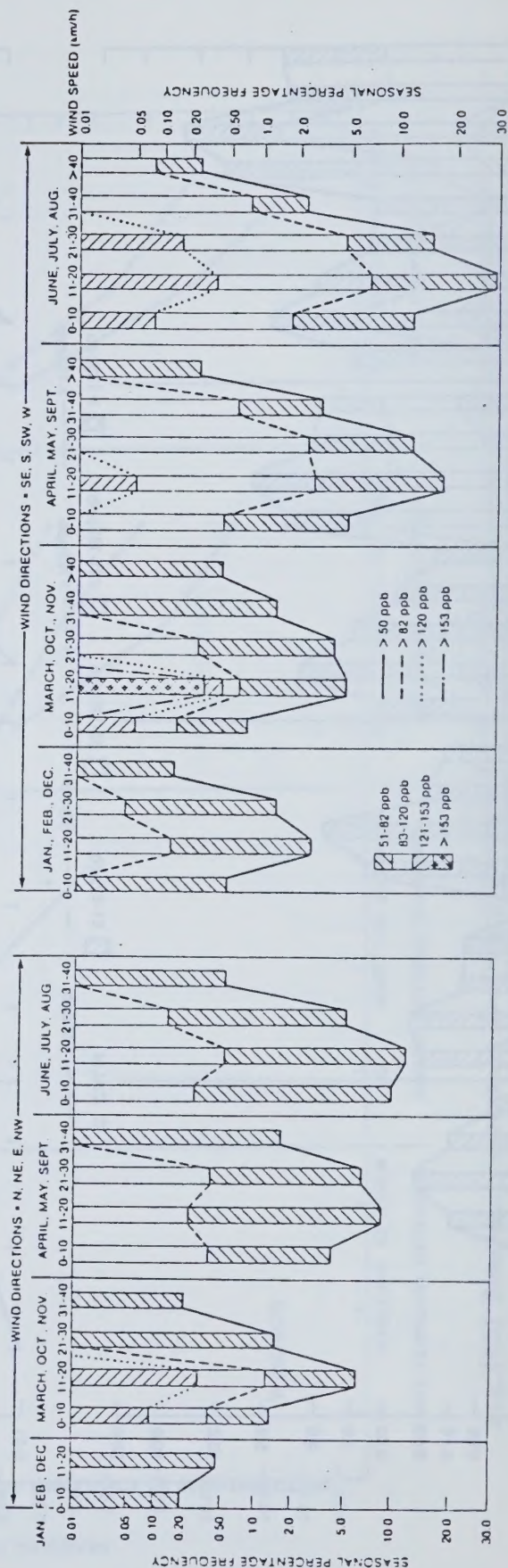


Fig.(23) Seasonal Percentage Frequency Distributions of Specified Hourly Wind Speed (km/hr) Classes for Two Wind Direction Groups (N, NE, E, NW and SE, S, SW, W) for Given Hourly Ozone Concentration Class Intervals at WINDSOR 1977 - 1980

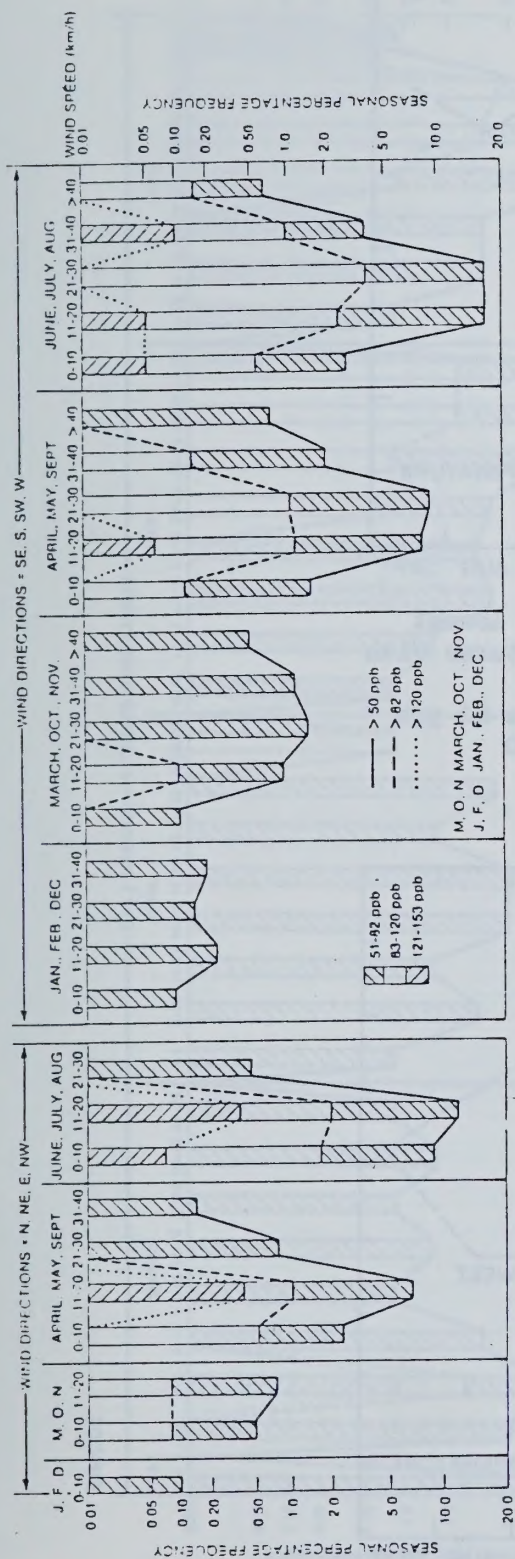


Fig.(24) Seasonal Percentage Frequency Distributions of Specified Hourly Wind Speed (km/hr) Classes for Two Wind Direction Groups (N, NE, E, NW and SE, S, SW, W) for Given Hourly Ozone Concentration Class Intervals at ST. CATHERINES 1977 - 1980

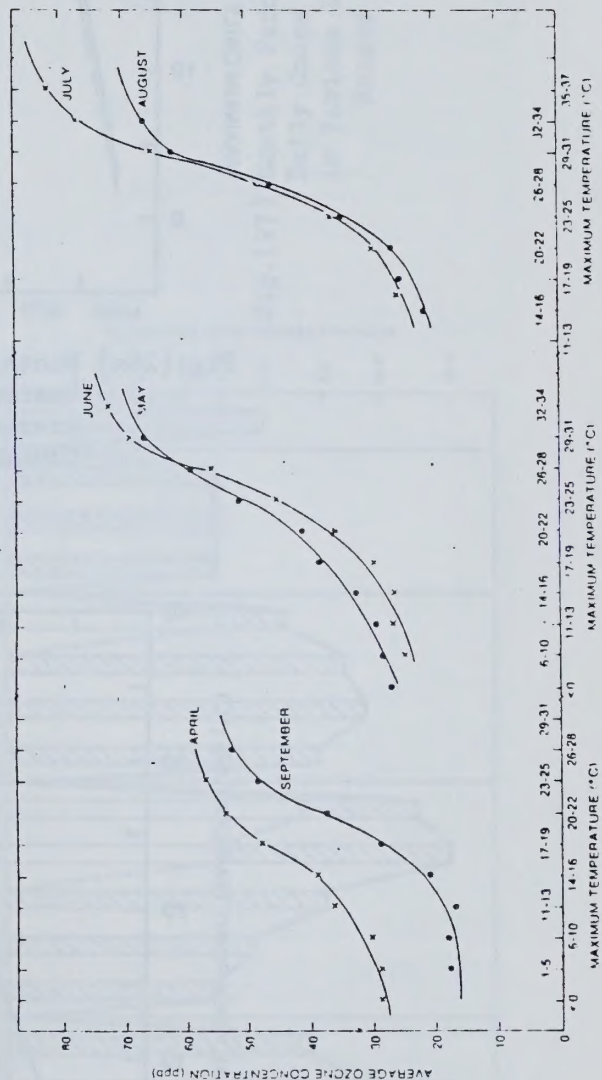


Fig.(25) Monthly Relationship Between Mean Daily Maximum Temperatures OC at Huron Park, Petrolia, Simcoe, St.Catherines and Stouffville and Corresponding Average Hourly Ozone Concentrations (1200-2100 EST) 1977 - 1980

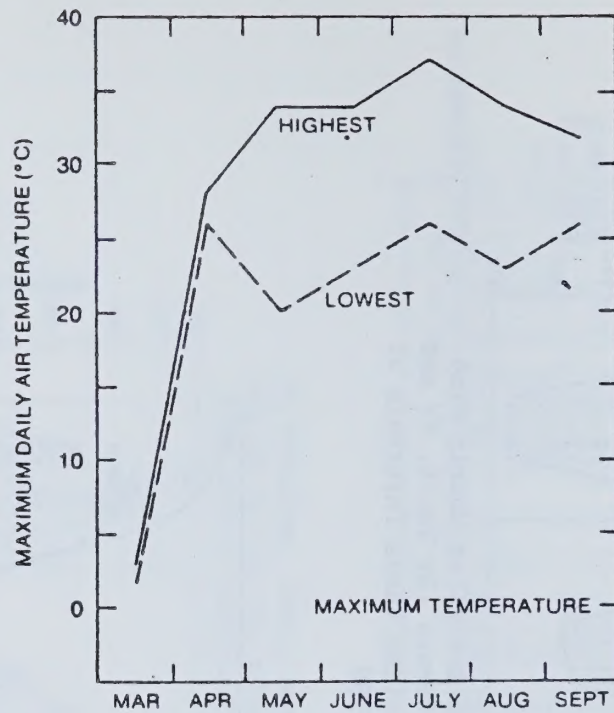


Fig.(26a) Monthly Highest and Lowest
Maximum Air Temperatures With
Average Daily Ozone
Concentrations above 82 ppb
1977 - 1980

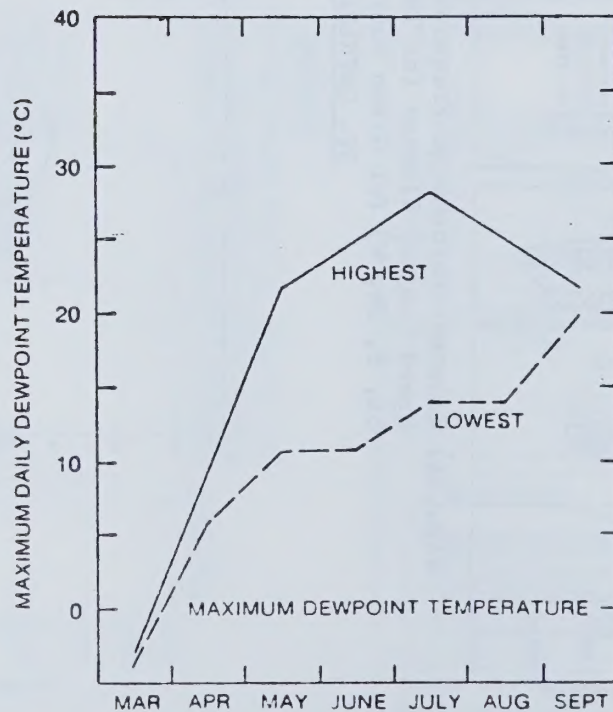


Fig.(26b) Monthly Highest and Lowest
Maximum Dewpoint Temp-
eratures With Average Daily
Ozone Concentrations Above
82 ppb 1977 - 1980

SIMCOE

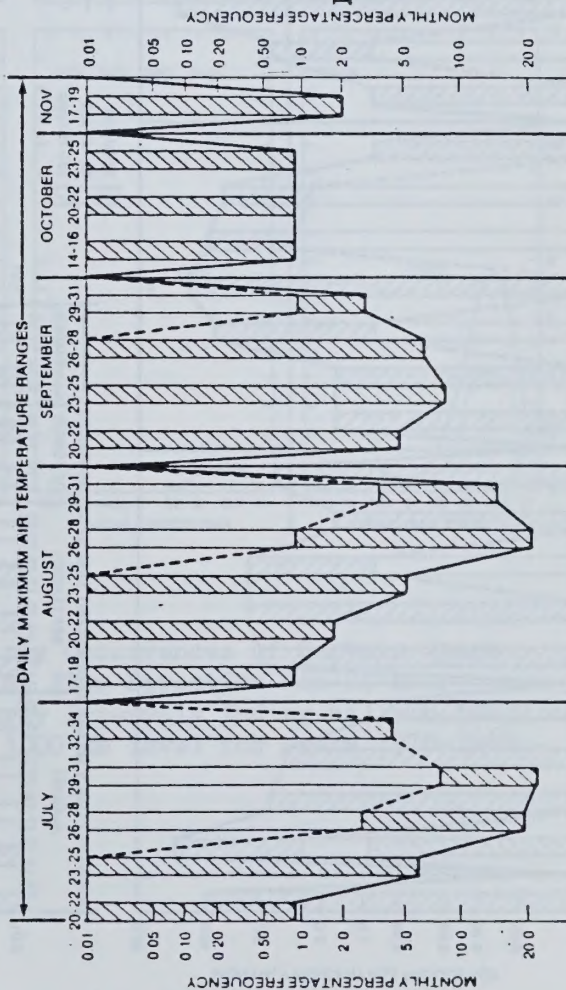
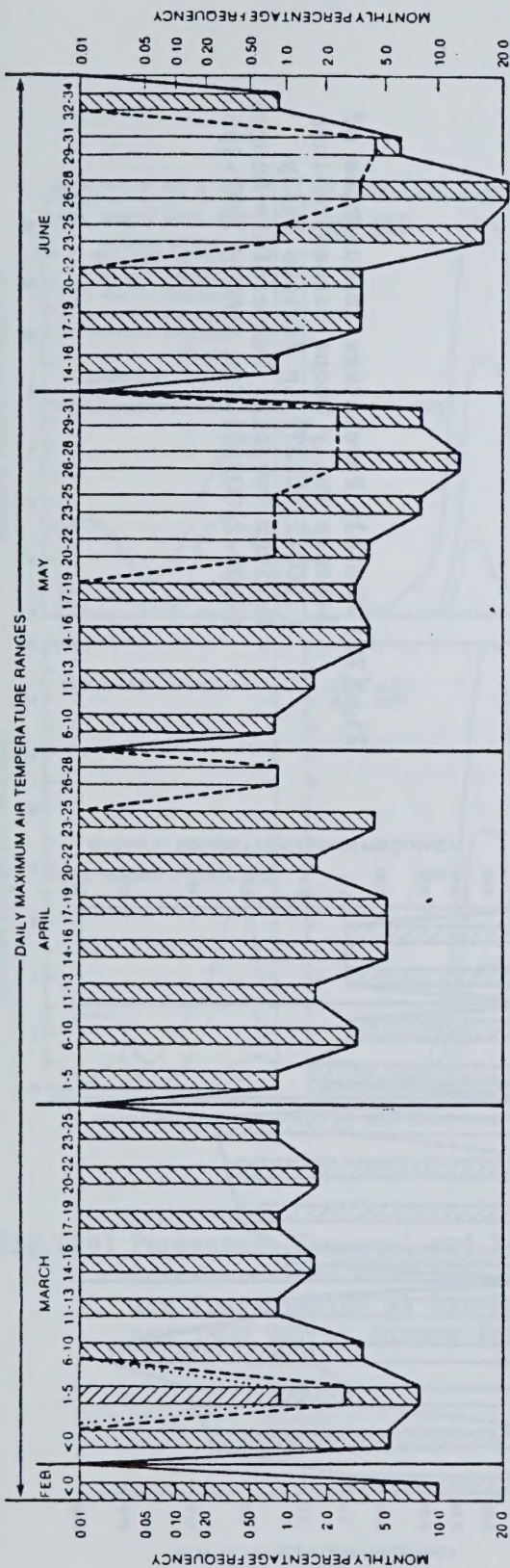


Fig.(27) Monthly Percentage Frequencies of Average Daily Ozone Concentrations (1200-2100EST) in Various Daily Maximum Air Temperature Ranges for SIMCOE 1977 - 1980

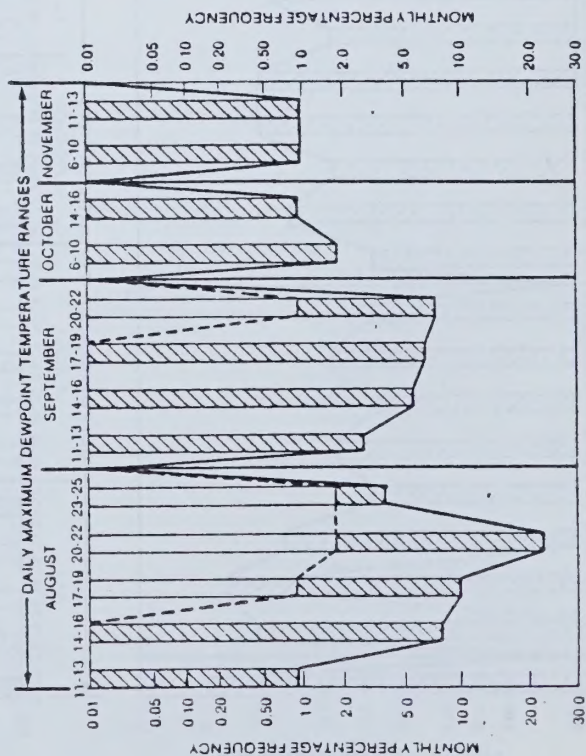
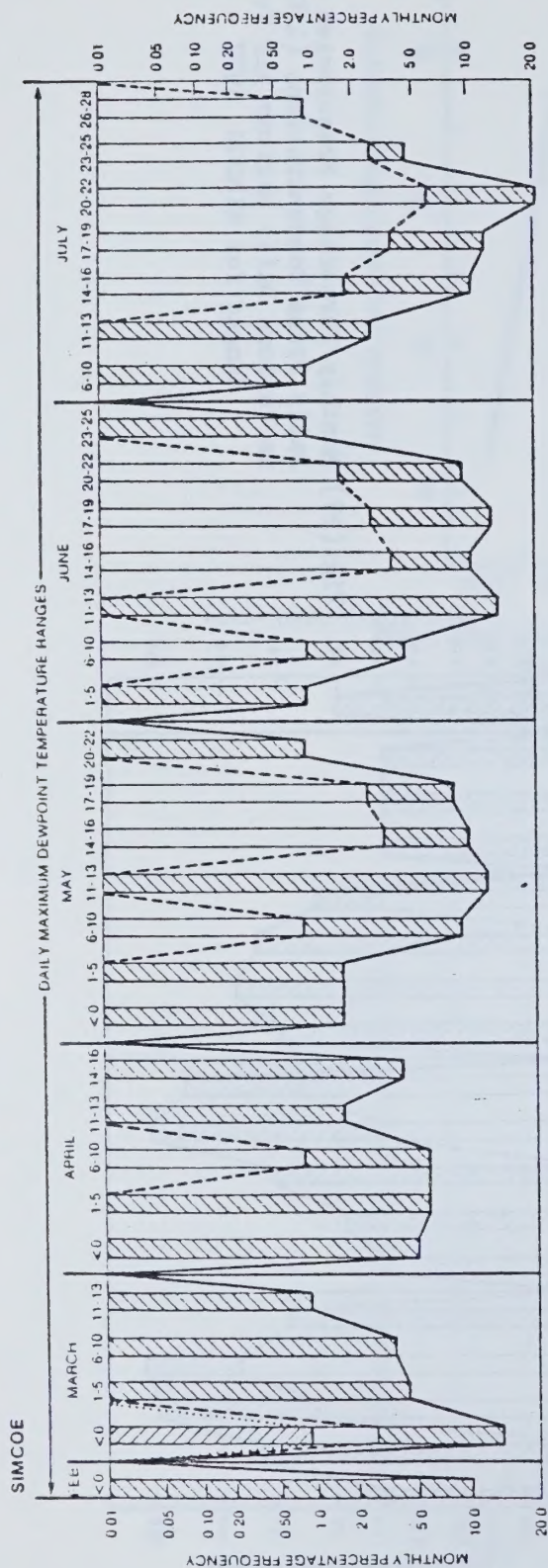


Fig.(28) Monthly Percentage Frequencies of
 Average Daily Ozone Concentrations
 (1200-2100EST) in Various Daily
 Maximum Dewpoint Temperature Ranges
 (0800-2400EST) for SIMCOE 1977-1980

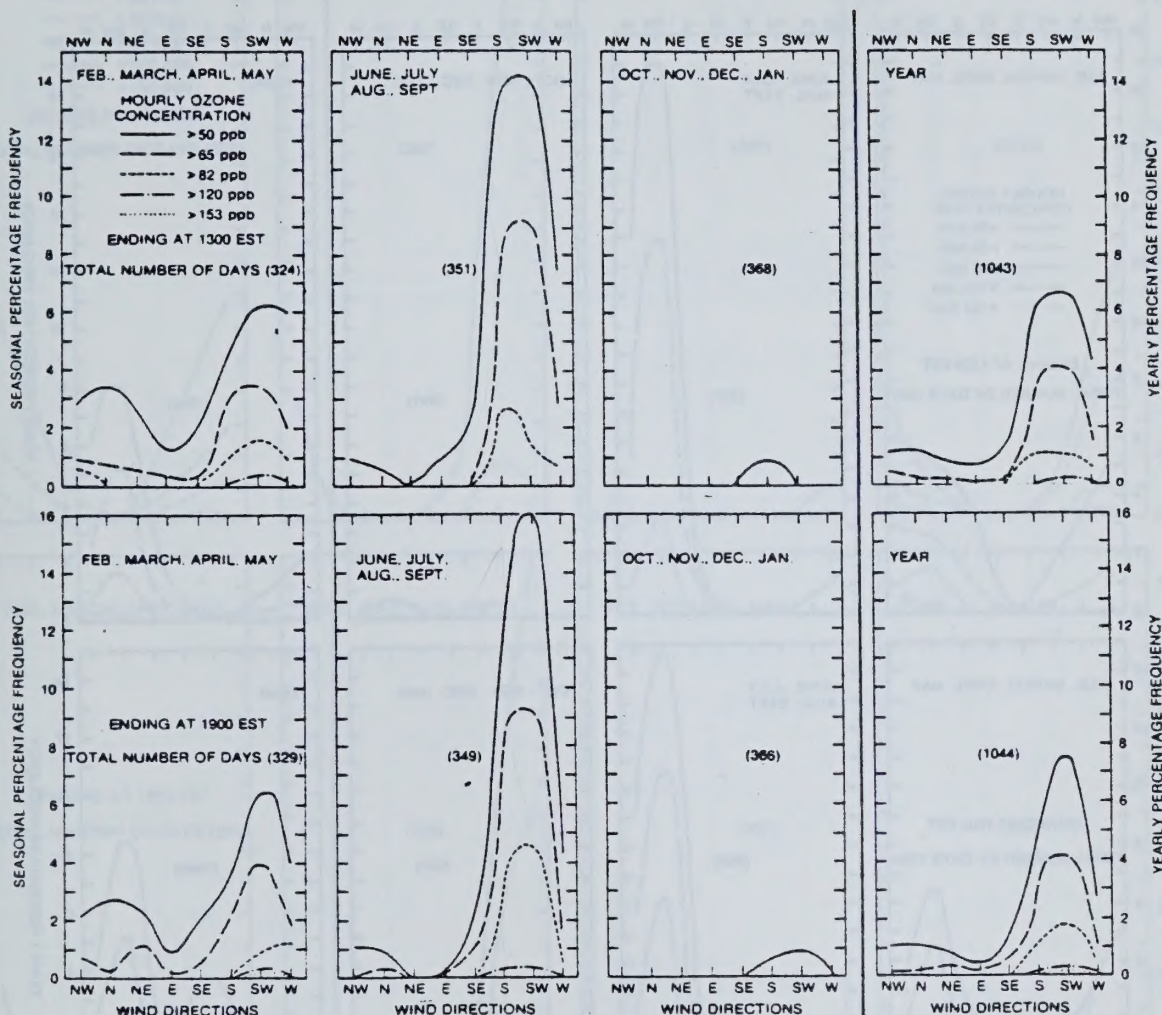


Fig.(29) Percentage Seasonal and Yearly Occurrences of Certain Ozone Concentrations with Resultant Flow Direction for 24-hour Air Trajectories at Six-Hourly Intervals Ending at 1900 EST and 1300 EST at Simcoe for 1000 mb level for years 1978-1980

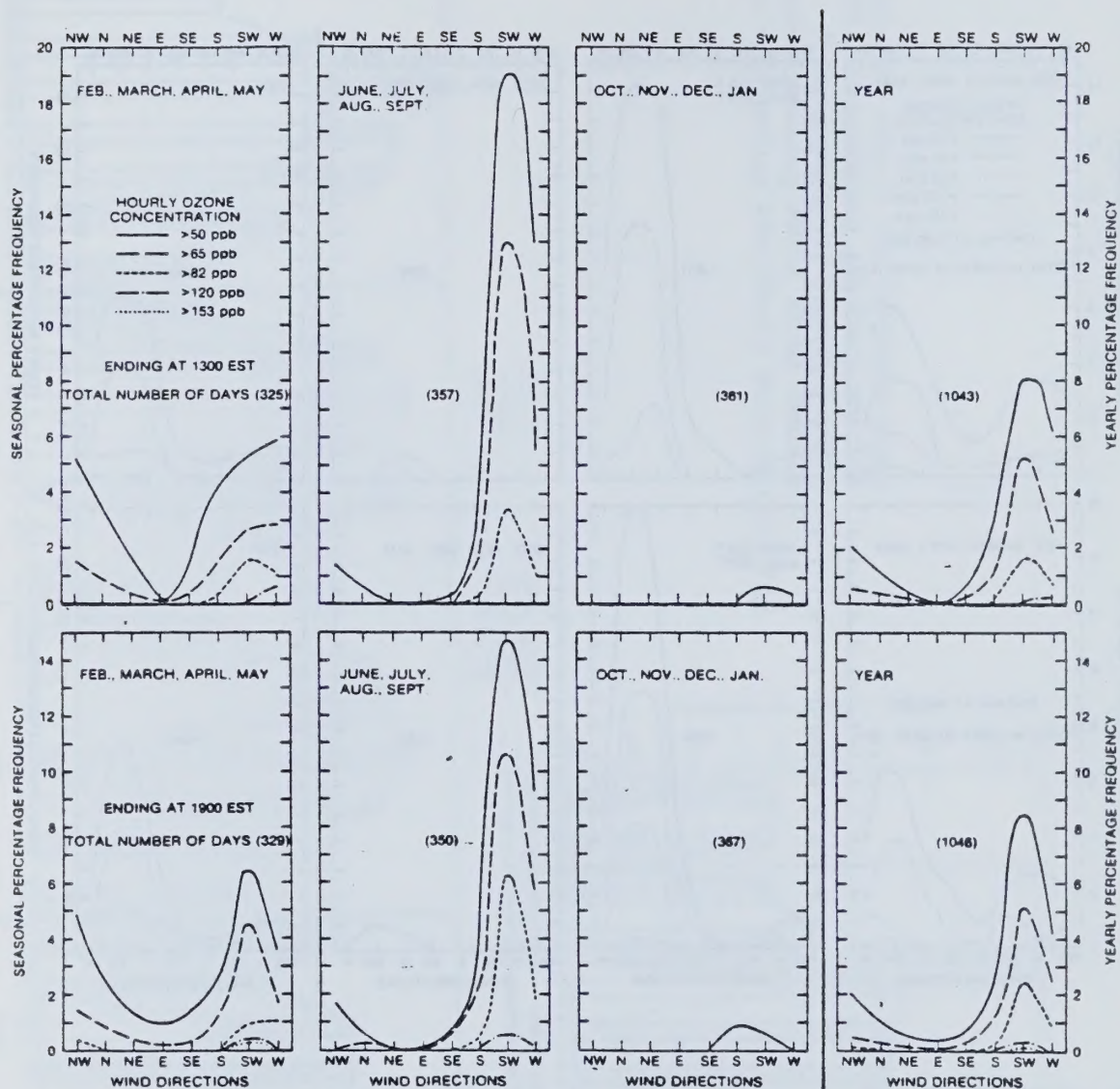


Fig.(30) Percentage Seasonal and Yearly Occurrences of Certain Ozone Concentrations With Resultant Flow Directions for 24-Hour Air Trajectories at Six-Hourly Intervals Ending at 1300 EST and 1900 EST at Simcoe for 925 mb level for years 1978-1980

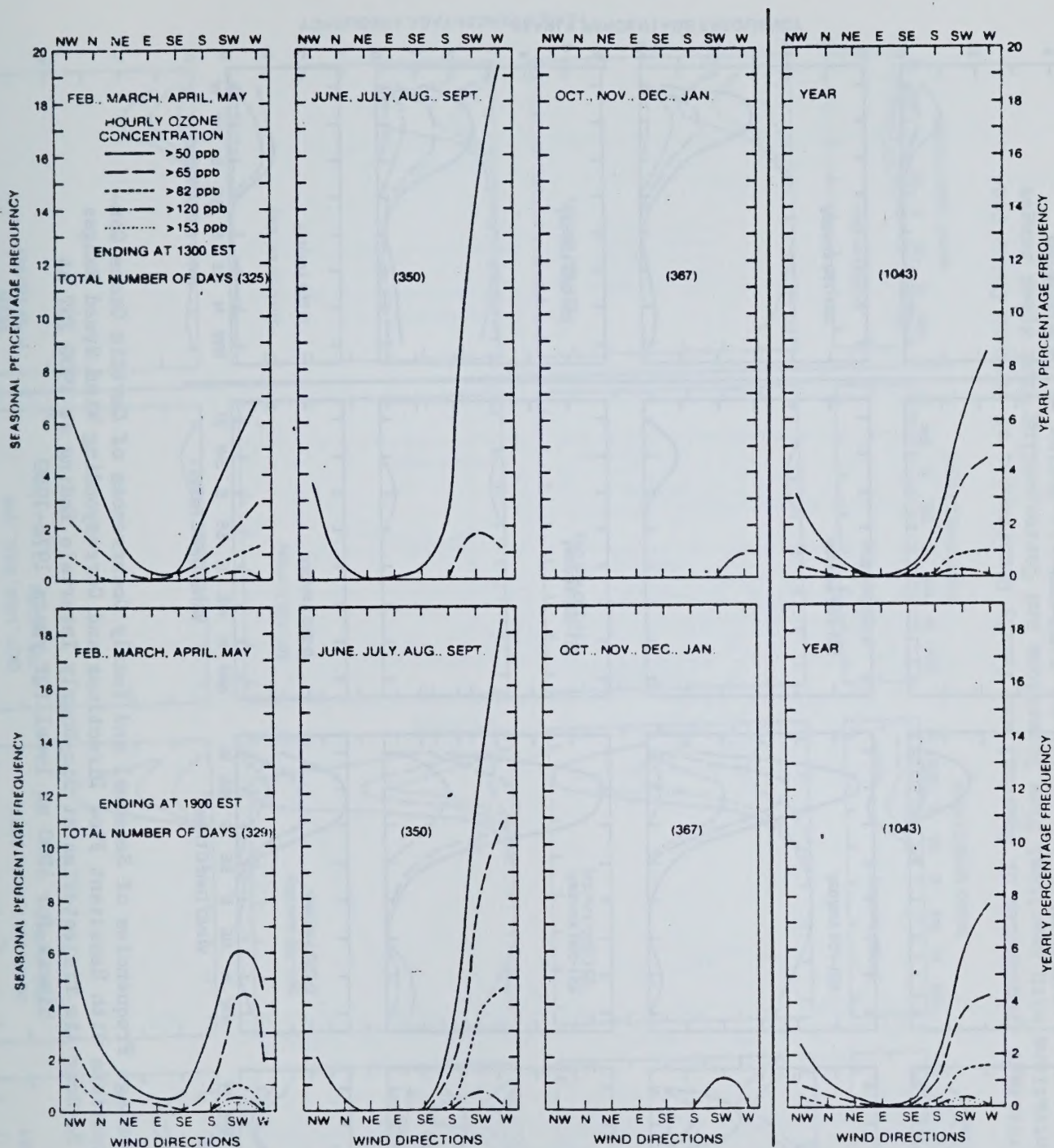


Fig.(31) Percentage Seasonal and Yearly Occurrences of Certain Ozone Concentrations(ppb) with Resultant Flow Directions for 24-hour Air Trajectories at Six-Hourly Intervals Ending at 1300 EST and 1900 EST at SIMCOE for 850 mb level for Years 1978 - 1980

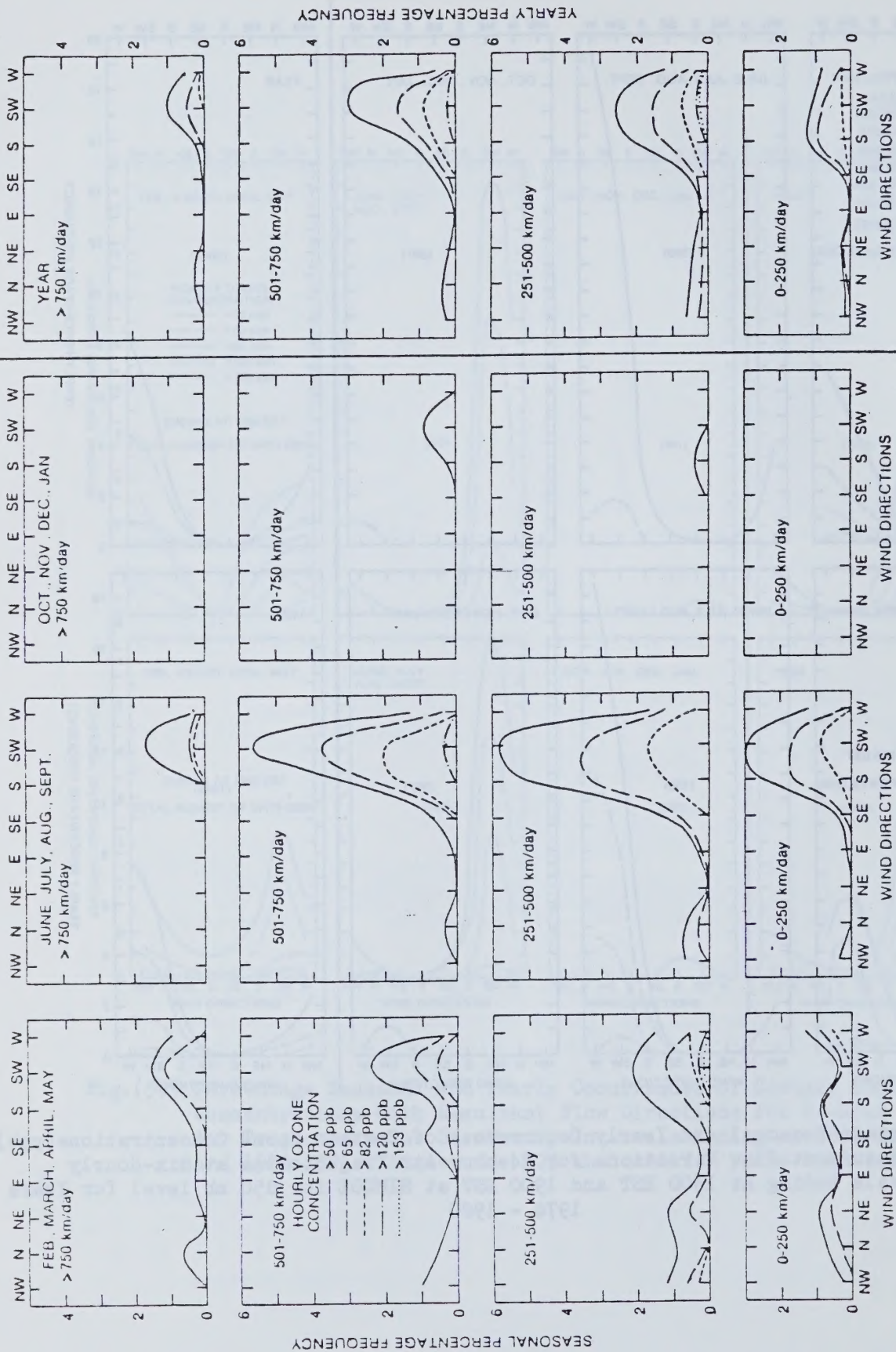


Fig.(32) Percentage Frequencies of Seasonal and Yearly Occurrences of Certain Ozone Concentrations with Resultant Flow Directions and Corresponding Wind Speed Ranges for 24-Hour Air Trajectories at Six-Hourly Intervals Ending at 1900 EST at Simcoe for 1000 mb level for years 1978-1980

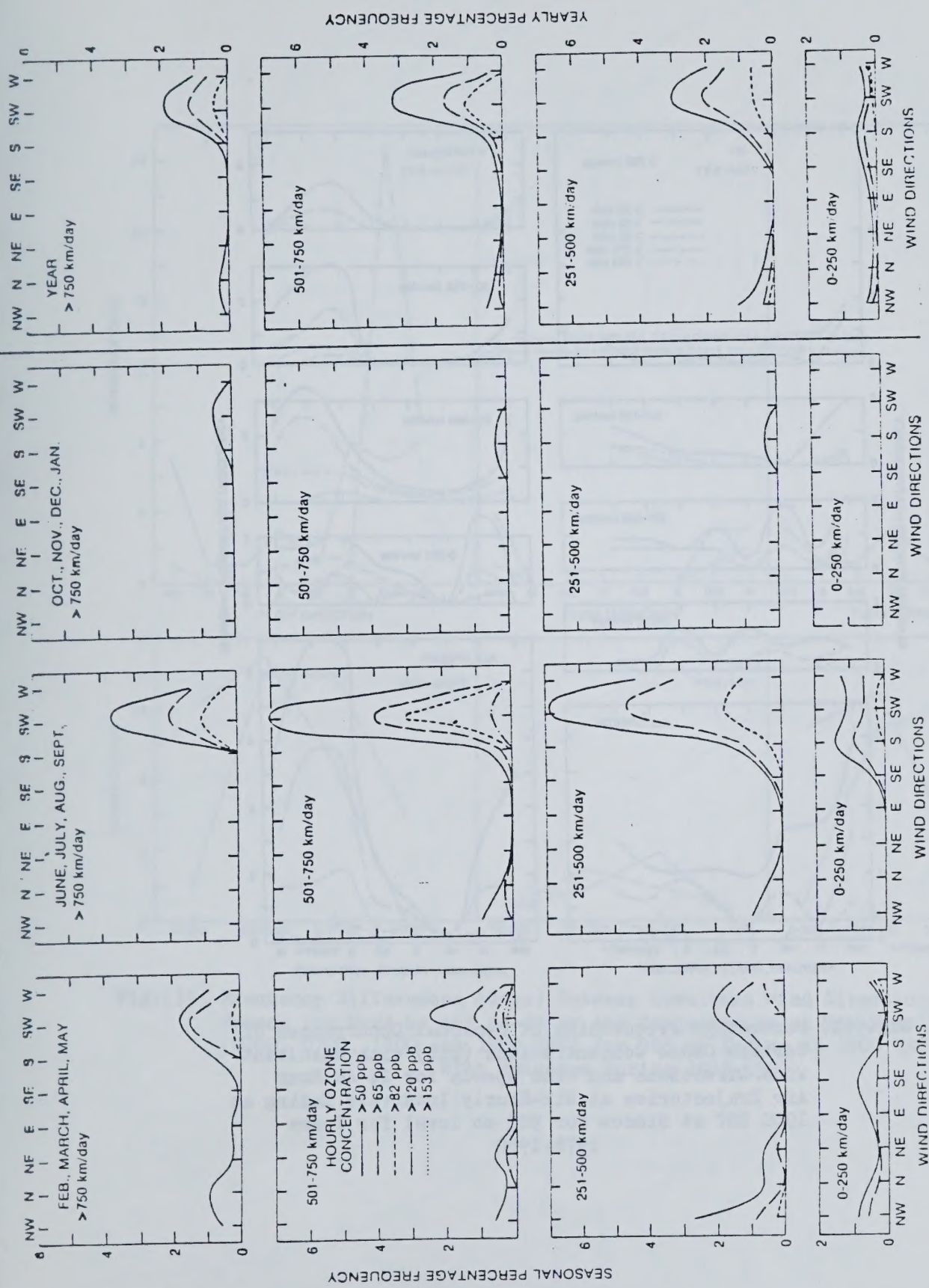


Fig.(33) Percentage Frequencies of Seasonal and Yearly Occurrences of Certain Ozone Concentrations with Resultant Flow Directions and Corresponding Wind Speed Ranges for 24-Hour Air Trajectories at Six-Hourly Intervals Ending at 1900 EST at Simcoe for 925 mb level for years 1978-1980

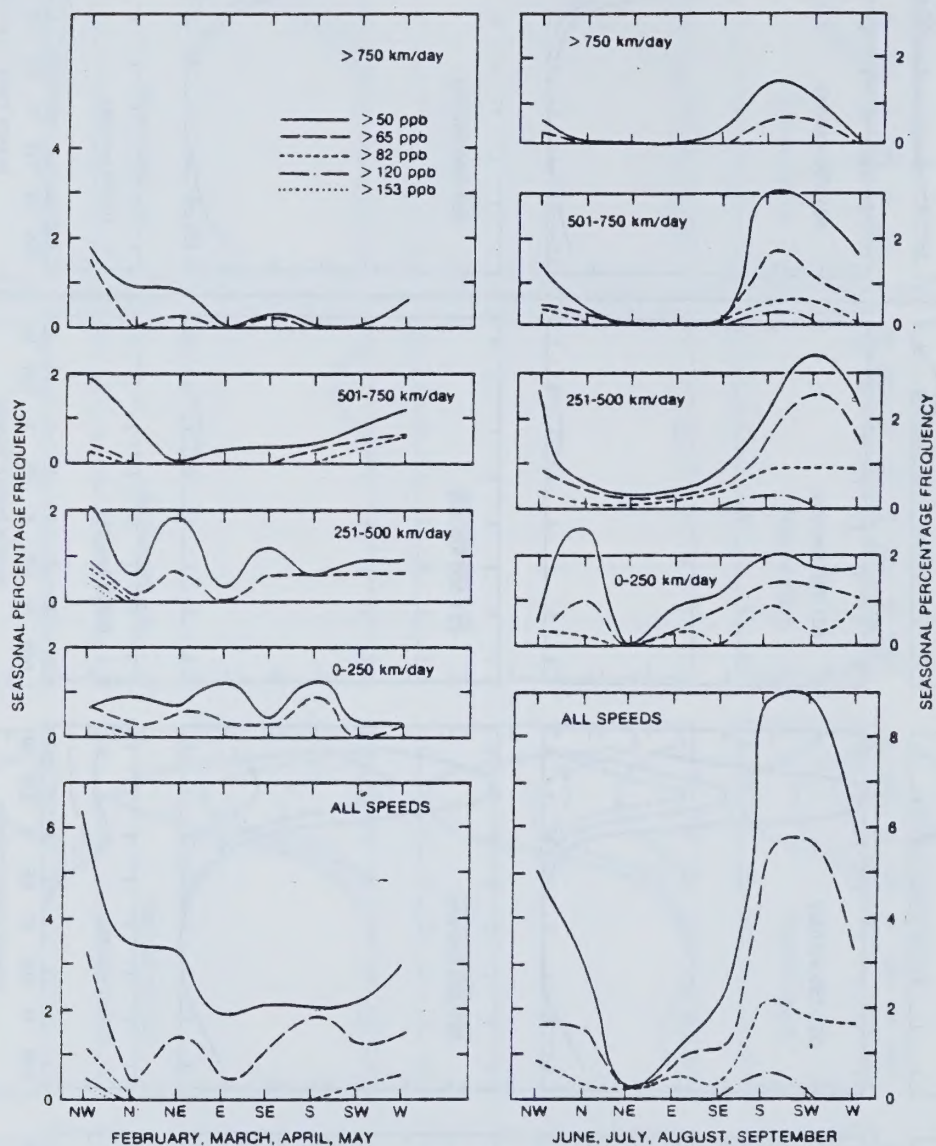


Fig.(34) Percentage Frequencies of Seasonal Occurrences of Certain Ozone Concentrations (ppb) with Resultant Wind Directions and Wind Speeds for 24-48 Hour Air Trajectories at Six-Hourly Intervals Ending at 1900 EST at Simcoe for 925 mb level for Years 1978-1980

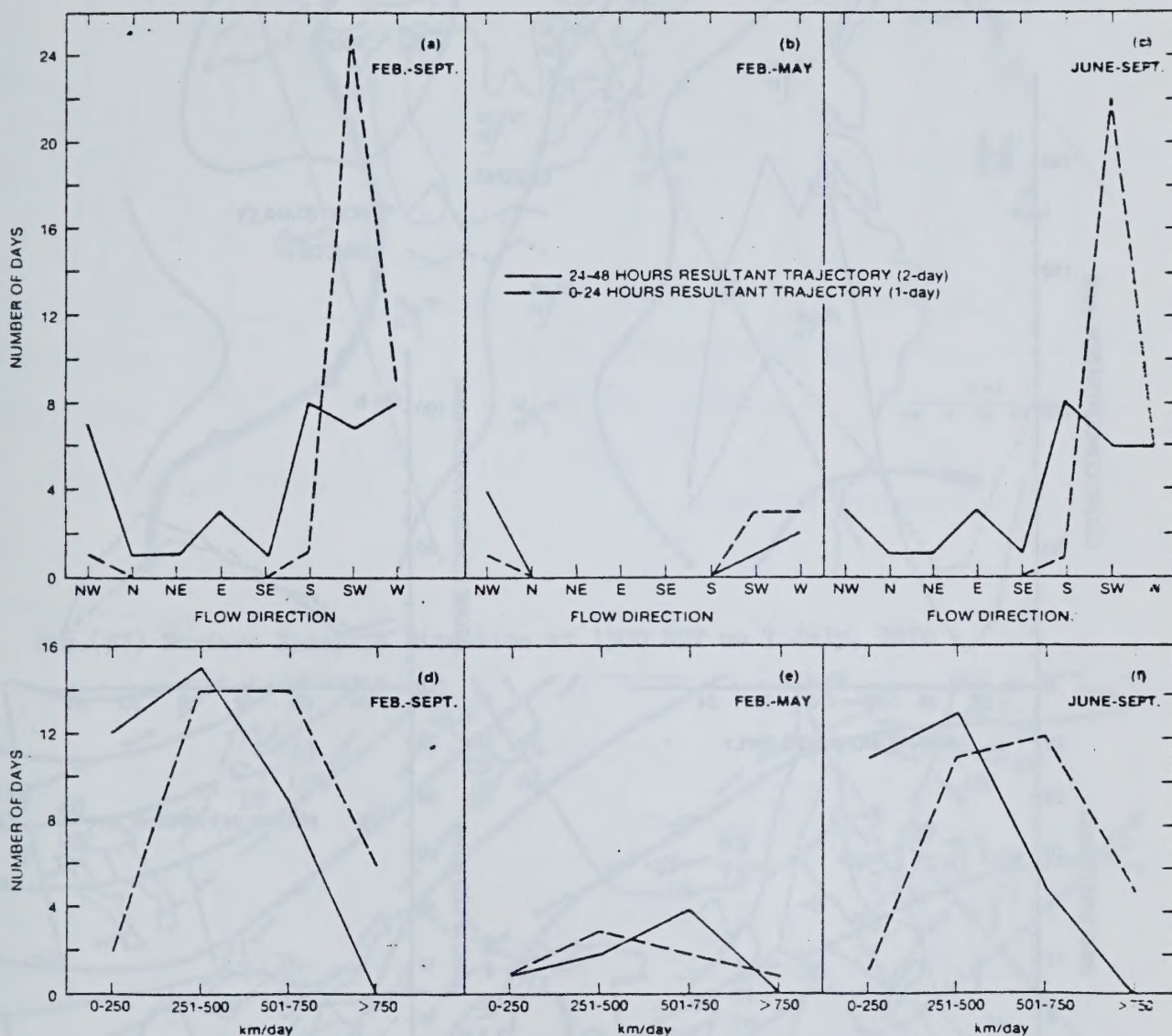


Fig.(35) Frequency Differences (days) Between Resultant Wind Directions and wind Speeds for 0-24 hr and 24-48 hr Air Trajectories at Six-Hourly Intervals (0100, 0700, 1300 and 1900 EST) for 925 mb Ending at 1900 EST at SIMCOB With Episodes During 1978-1980

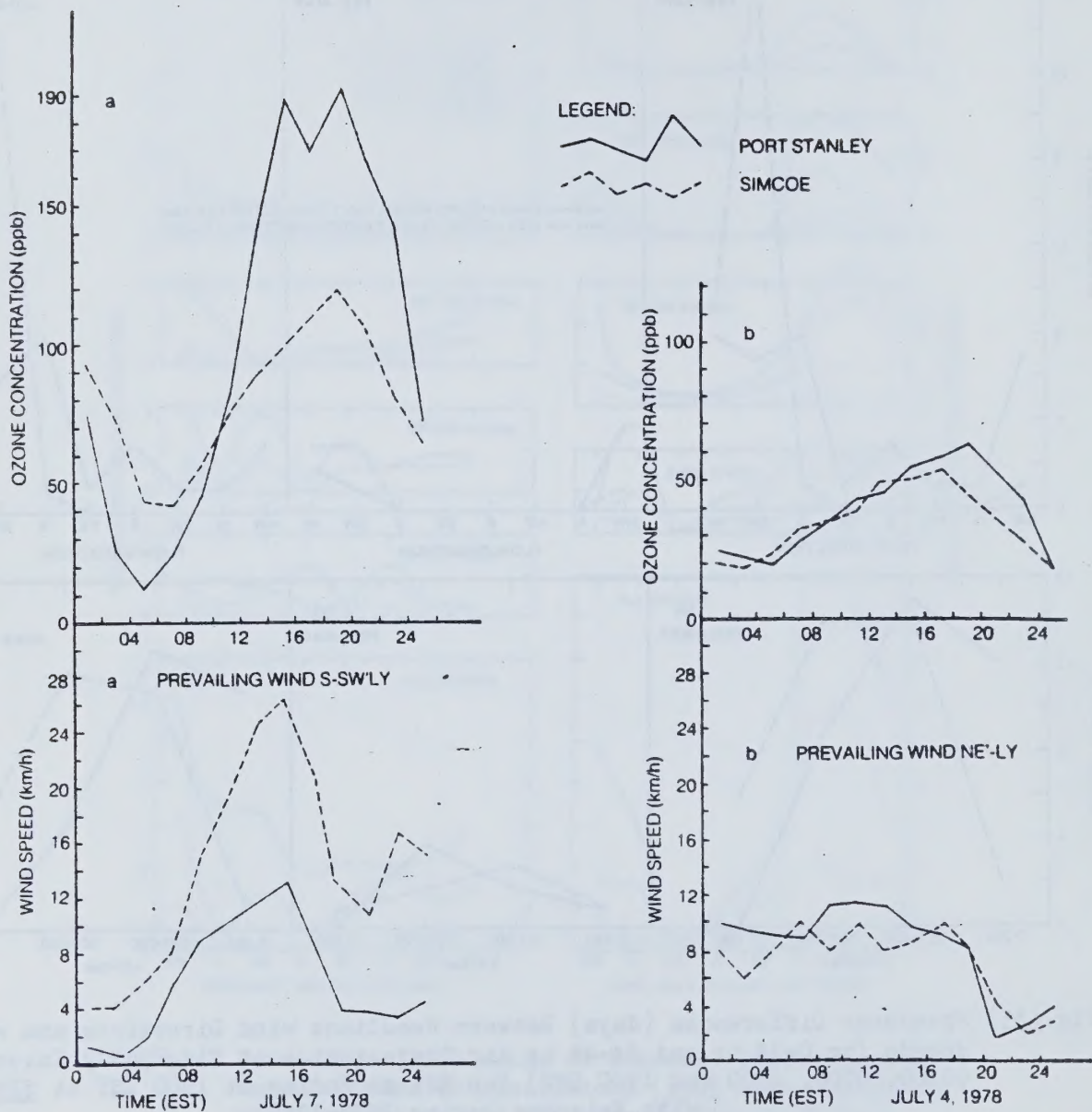


Fig.(36) Diurnal Variation of Hourly Ozone Concentrations (ppb), Wind Speed (km/hr) and Daytime Prevailing Wind Direction on 4 and 7 July, 1978 at Simcoe and Port Stanley

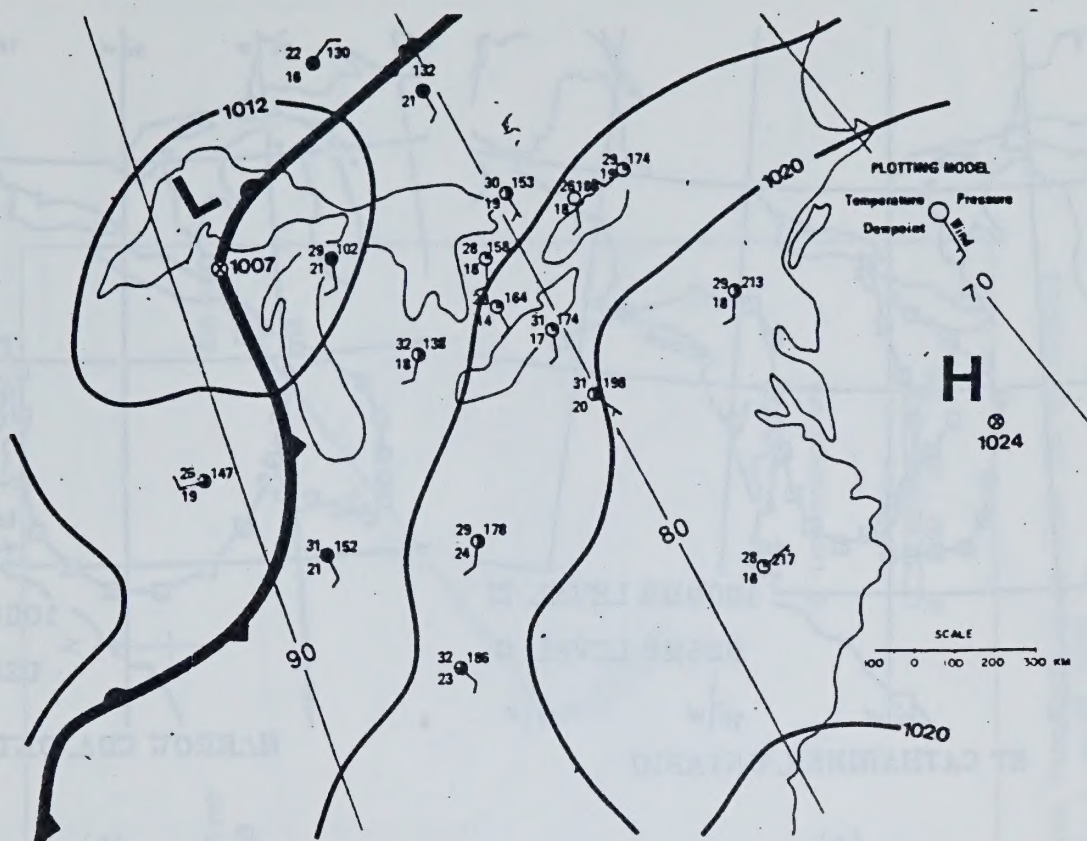


Fig.(37) Surface Synoptic Situation at 1300 EST on 7 July, 1978

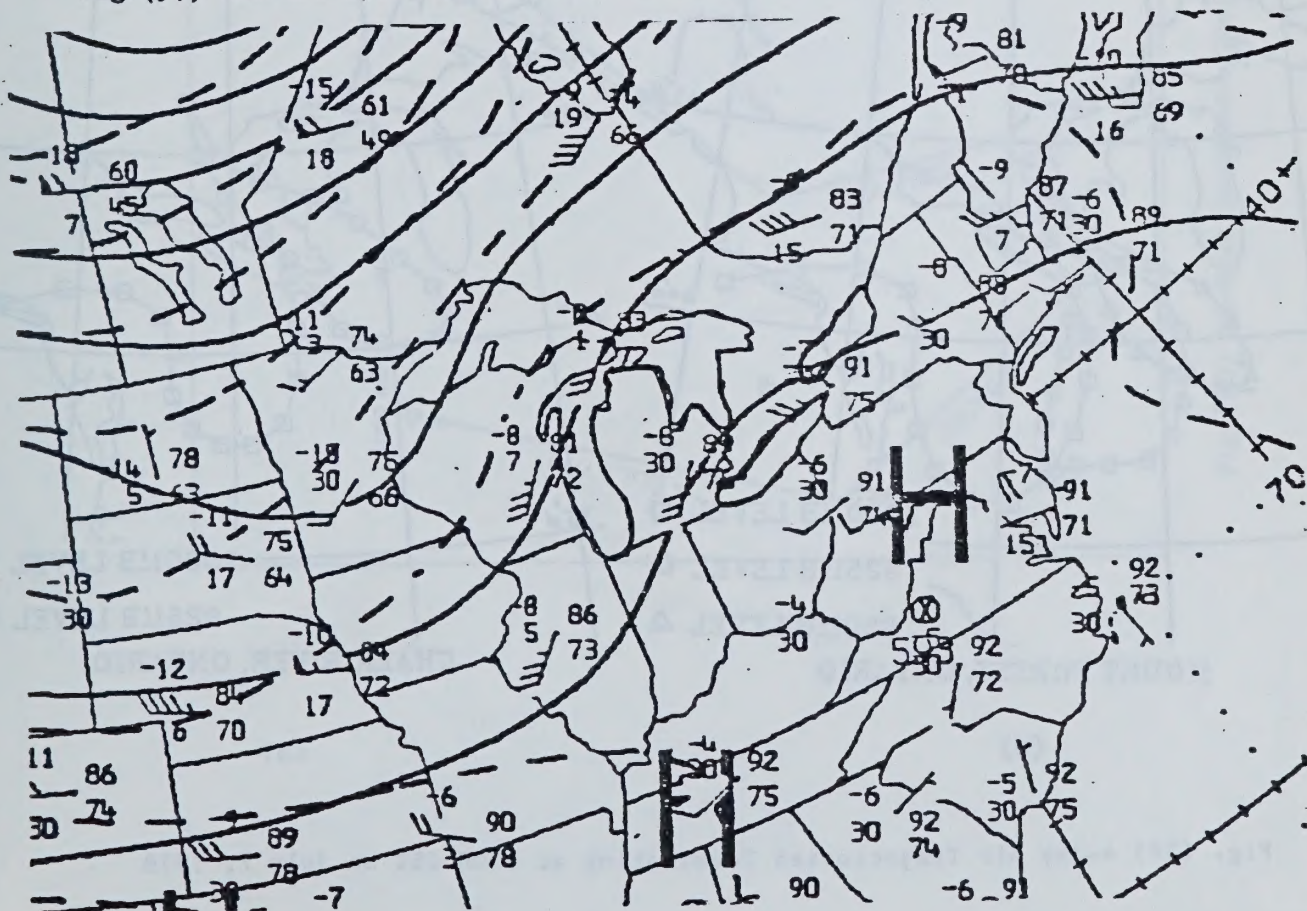
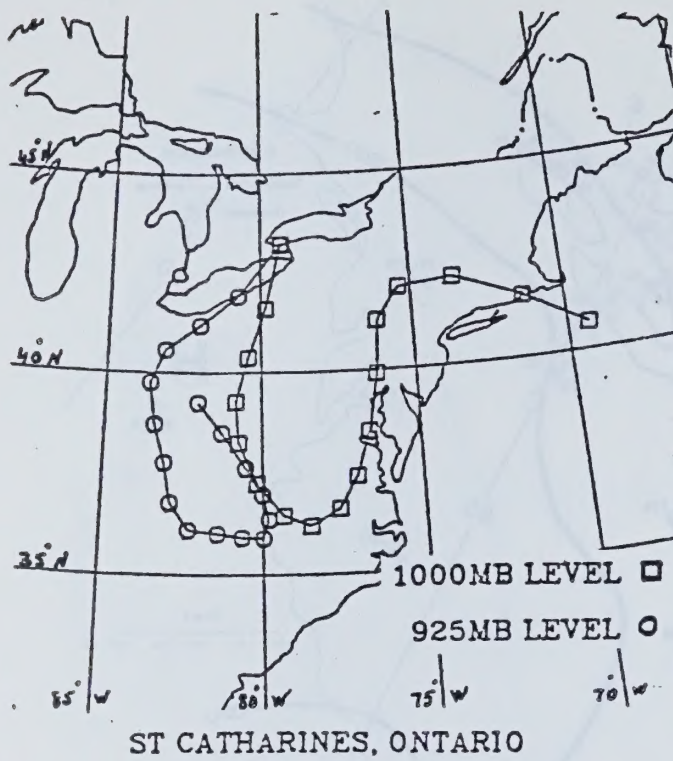
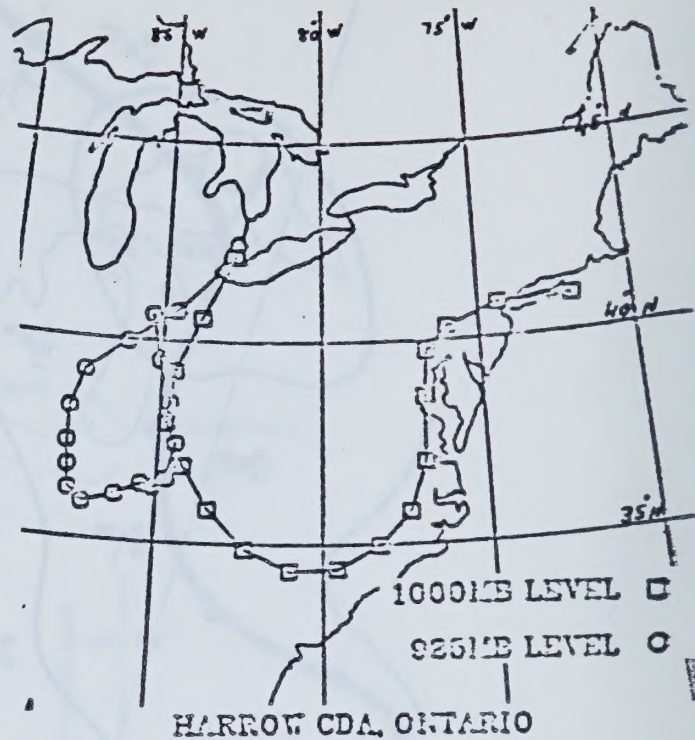


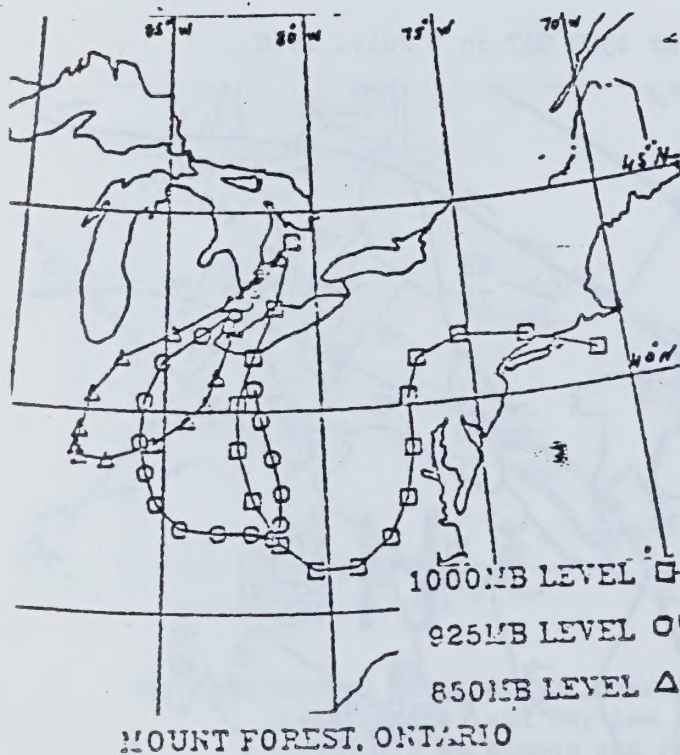
Fig. 38 500 mb synoptic situation at 0700 EST on July 7, 1978



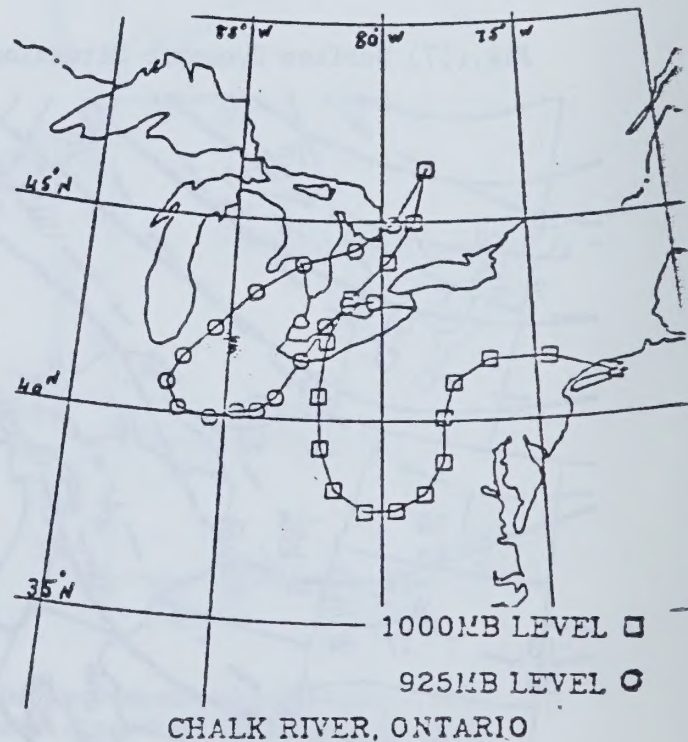
(a)



(b)



(c)



(d)

Fig. (39) 4-day Air Trajectories Terminating at 1900 EST on July 7, 1978

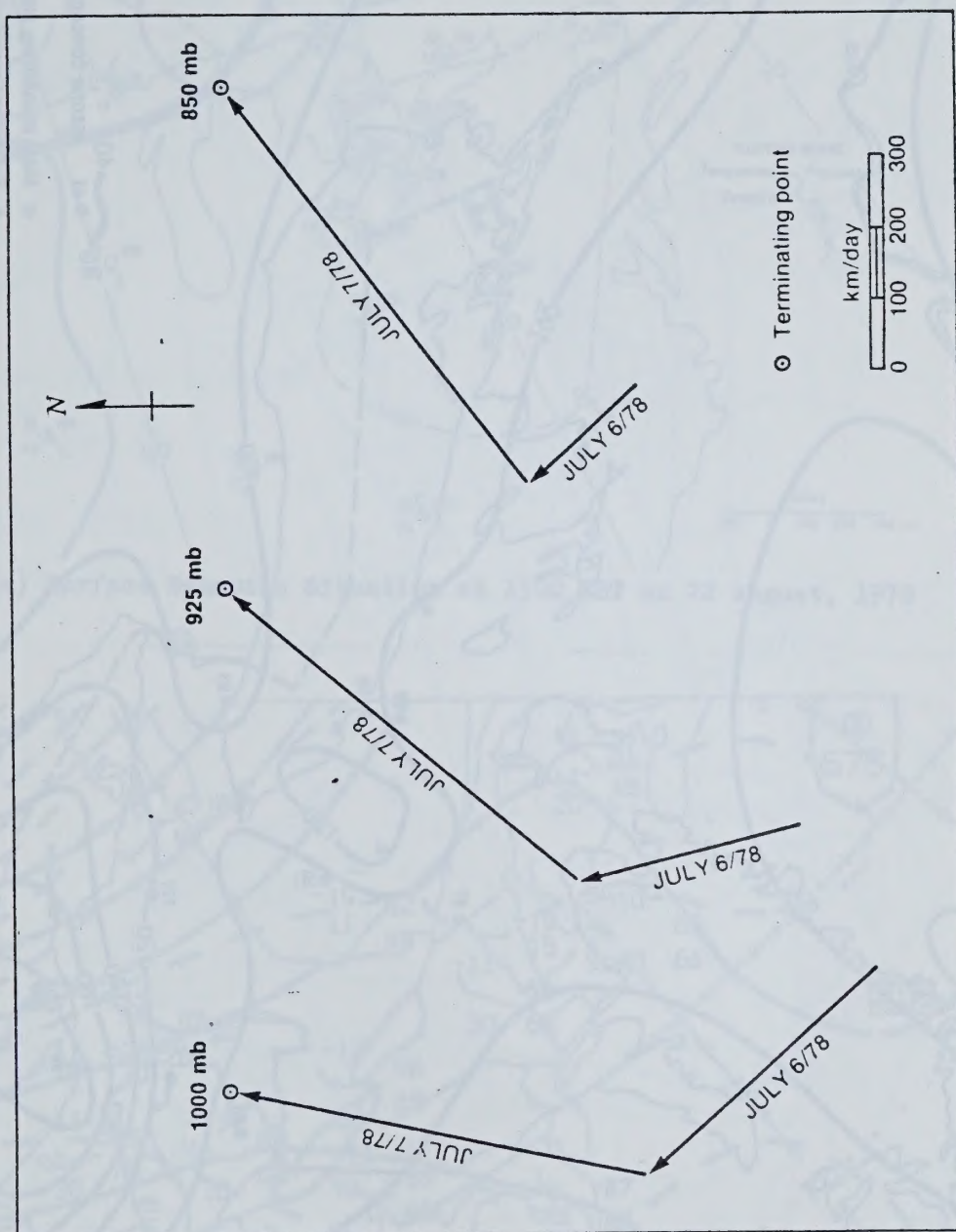


Fig.(40) 24-Hour Resultant Trajectories Terminating at 1900 EST at SIMCOE
July 6 and 7 1978

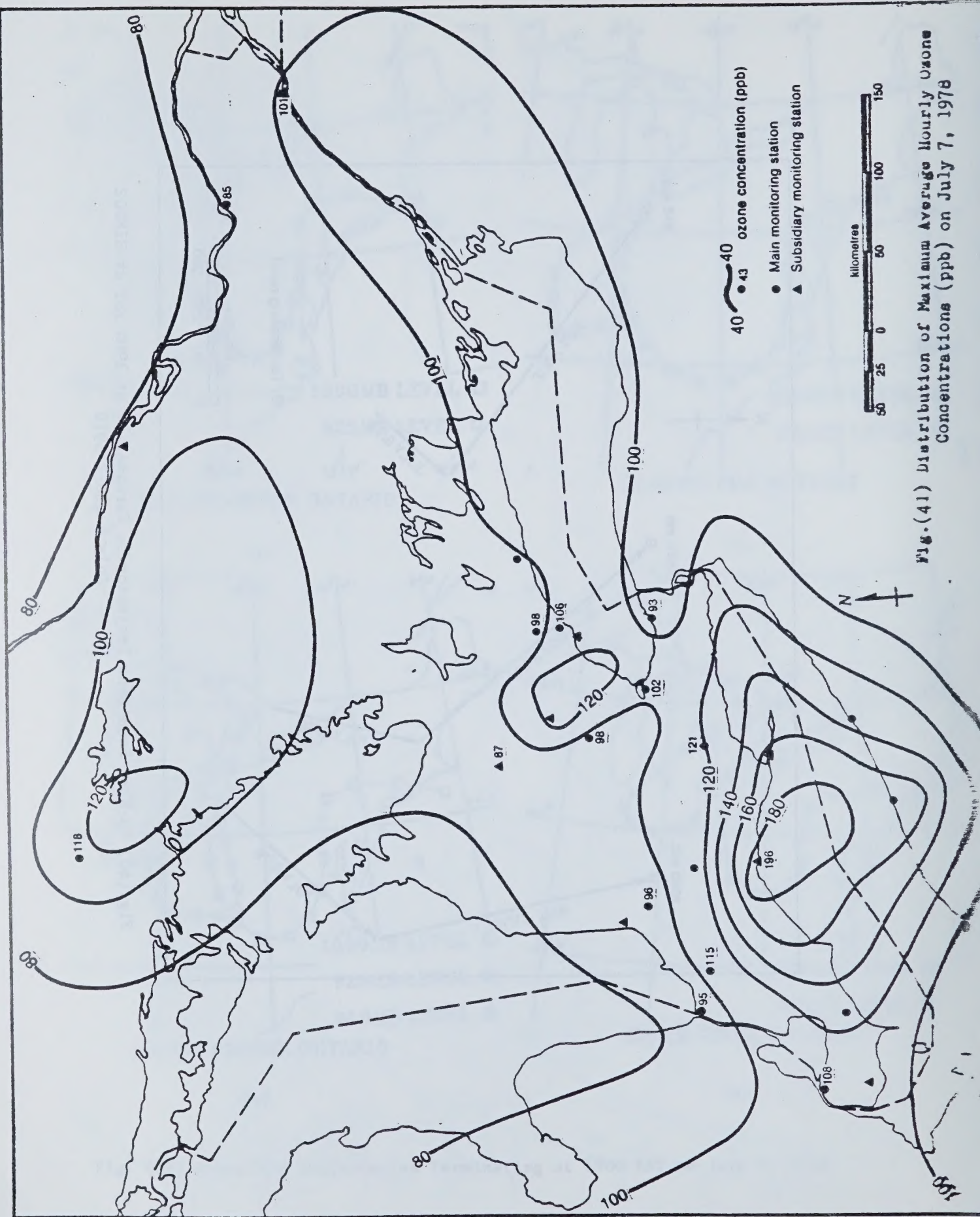
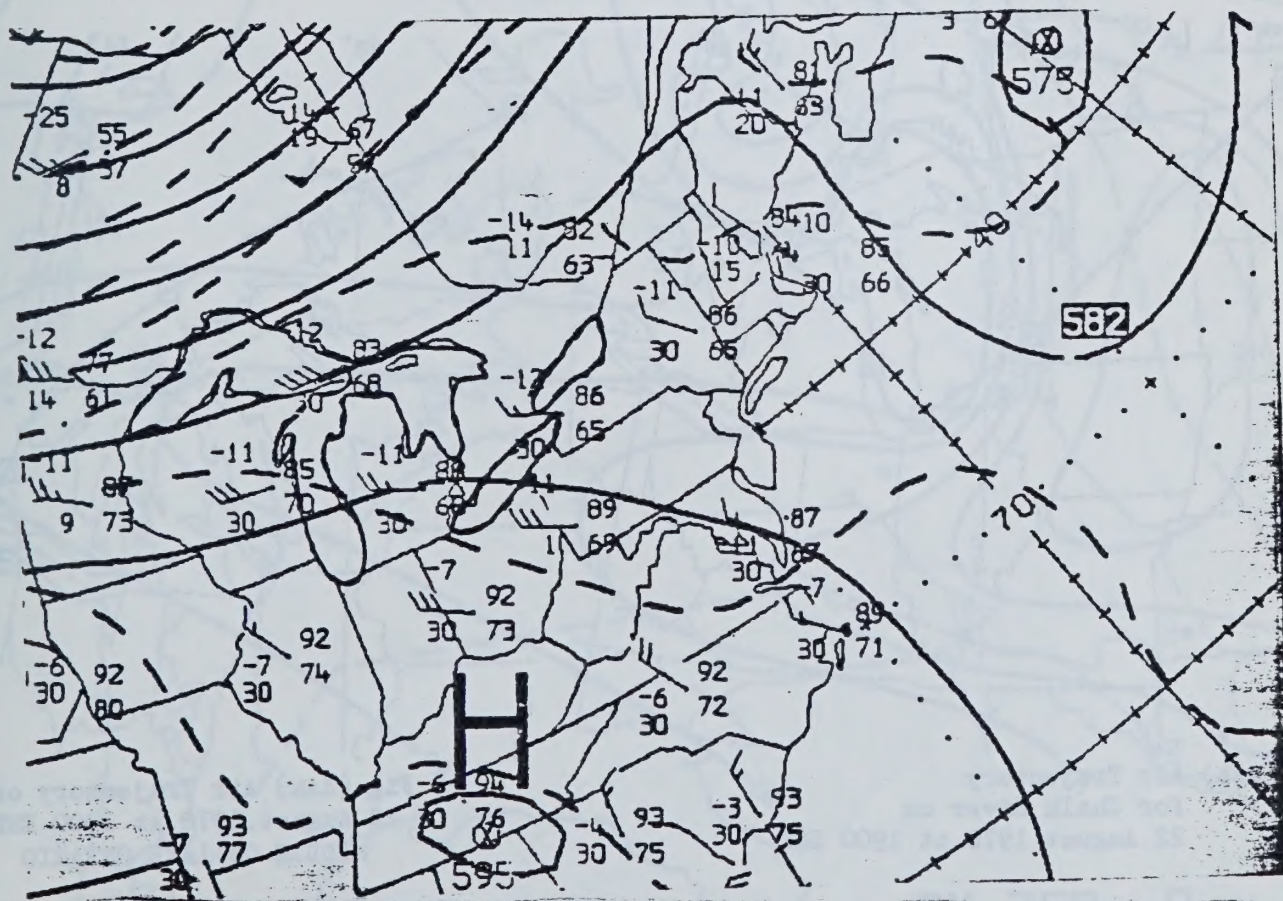
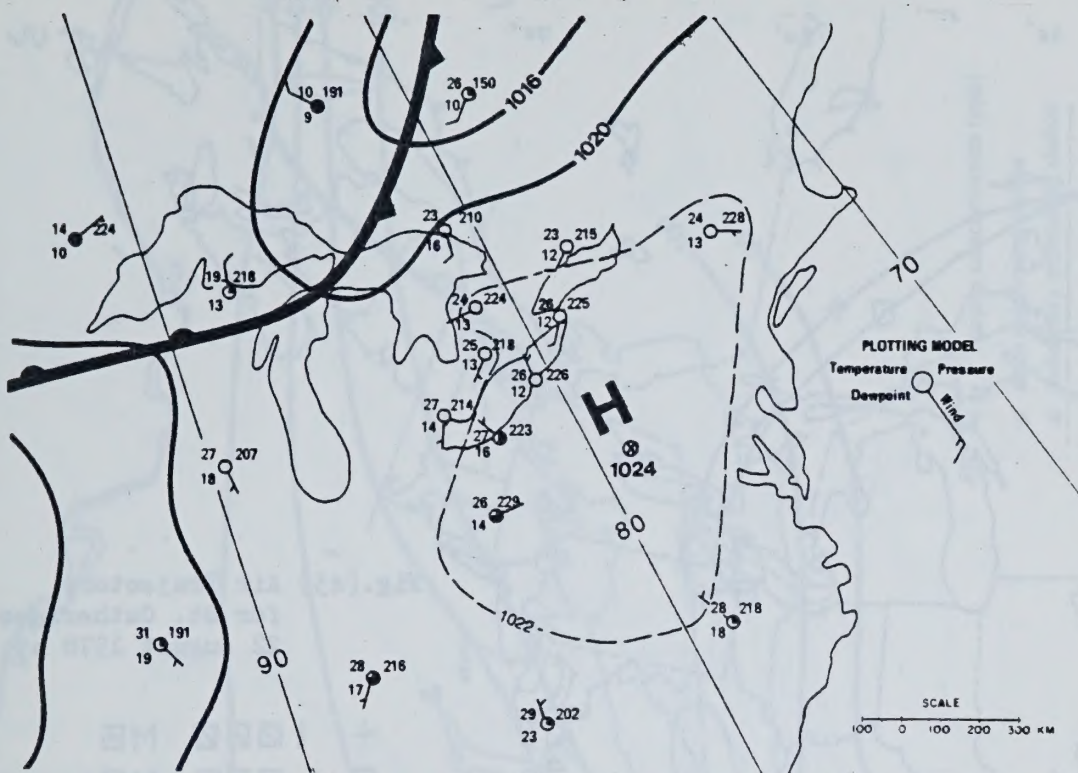


Fig. (41) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on July 7, 1978



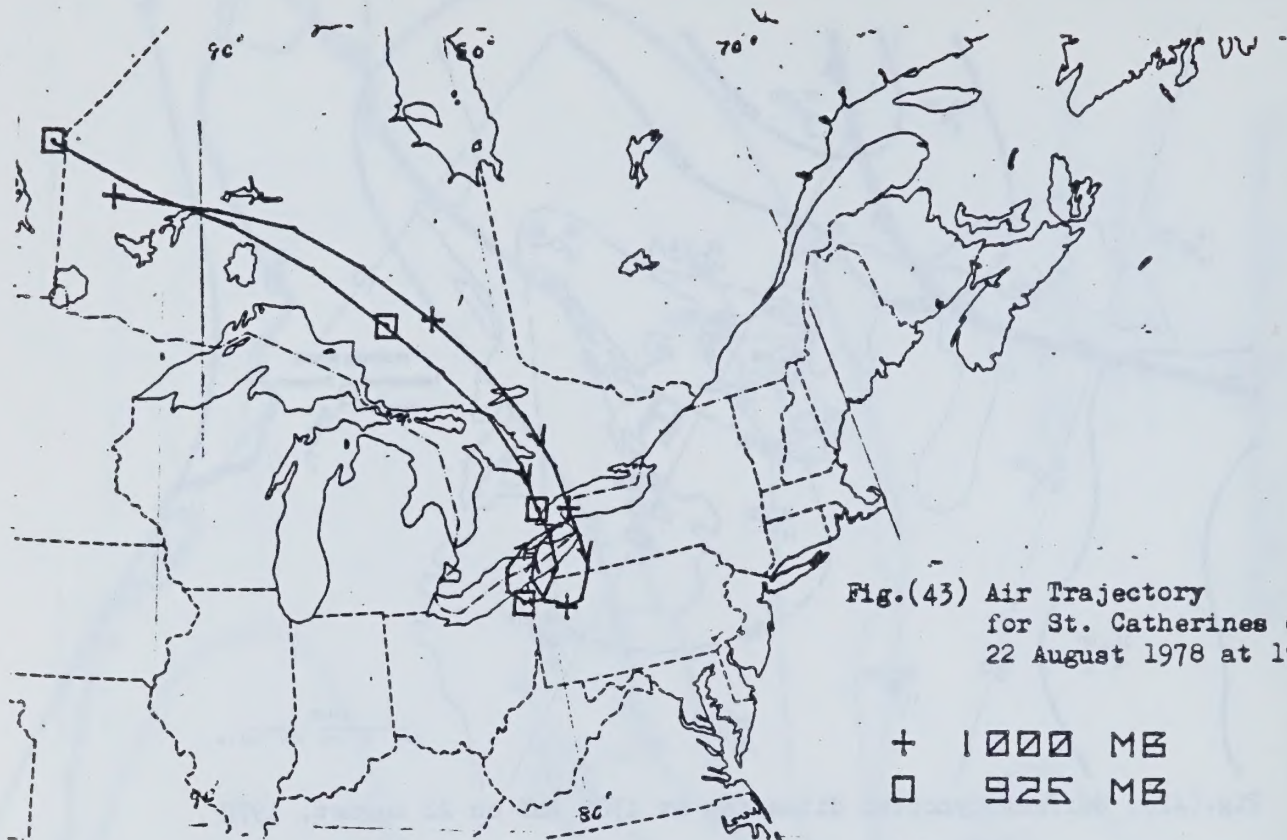


Fig.(43) Air Trajectory
for St. Catharines on
22 August 1978 at 1900 EST

+ 1000 MB
□ 925 MB

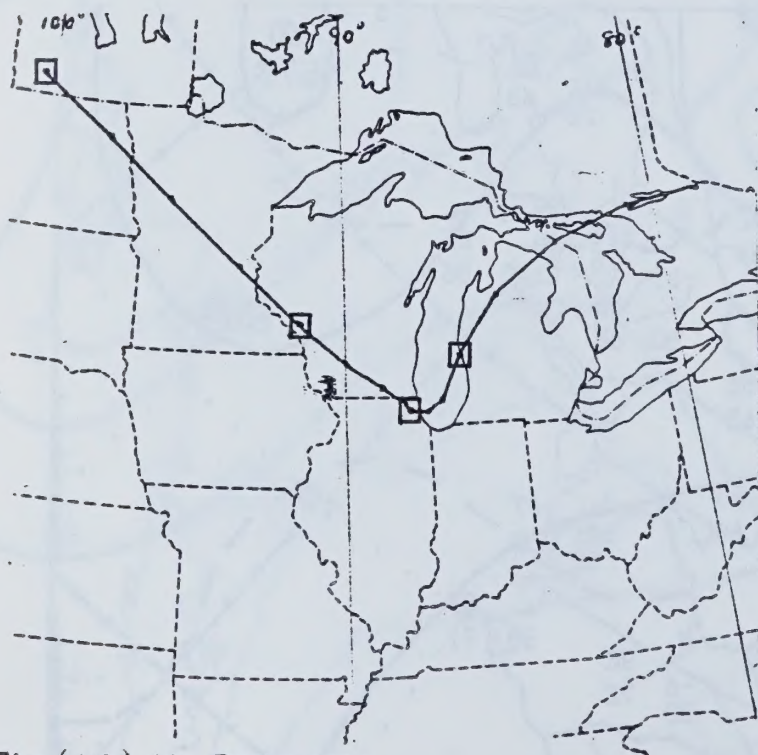


Fig.(44b) Air Trajectory
for Chalk River on
22 August 1978 at 1900 EST

□ 925 MB

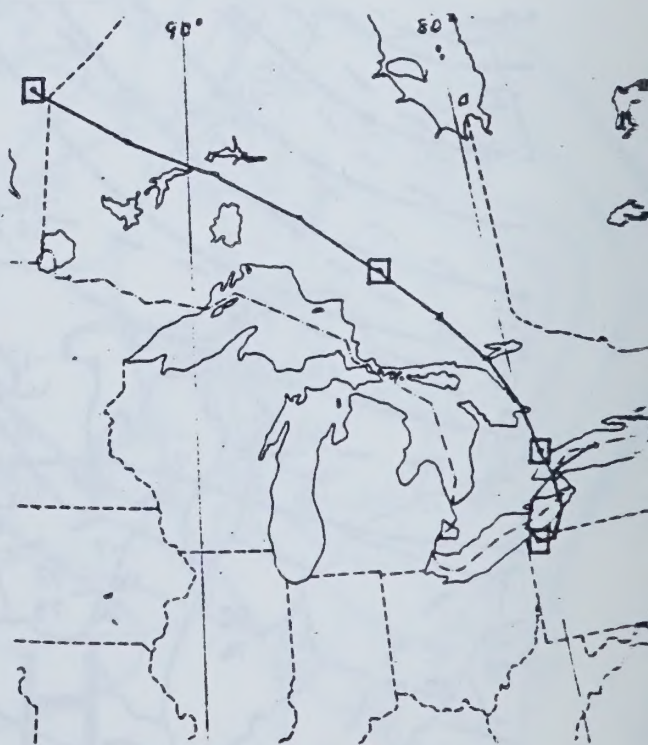


Fig.(44a) Air Trajectory on
22 August, 1978 at 1900 EST
MIDDLE OF LAKE ONTARIO

□ 925 MB

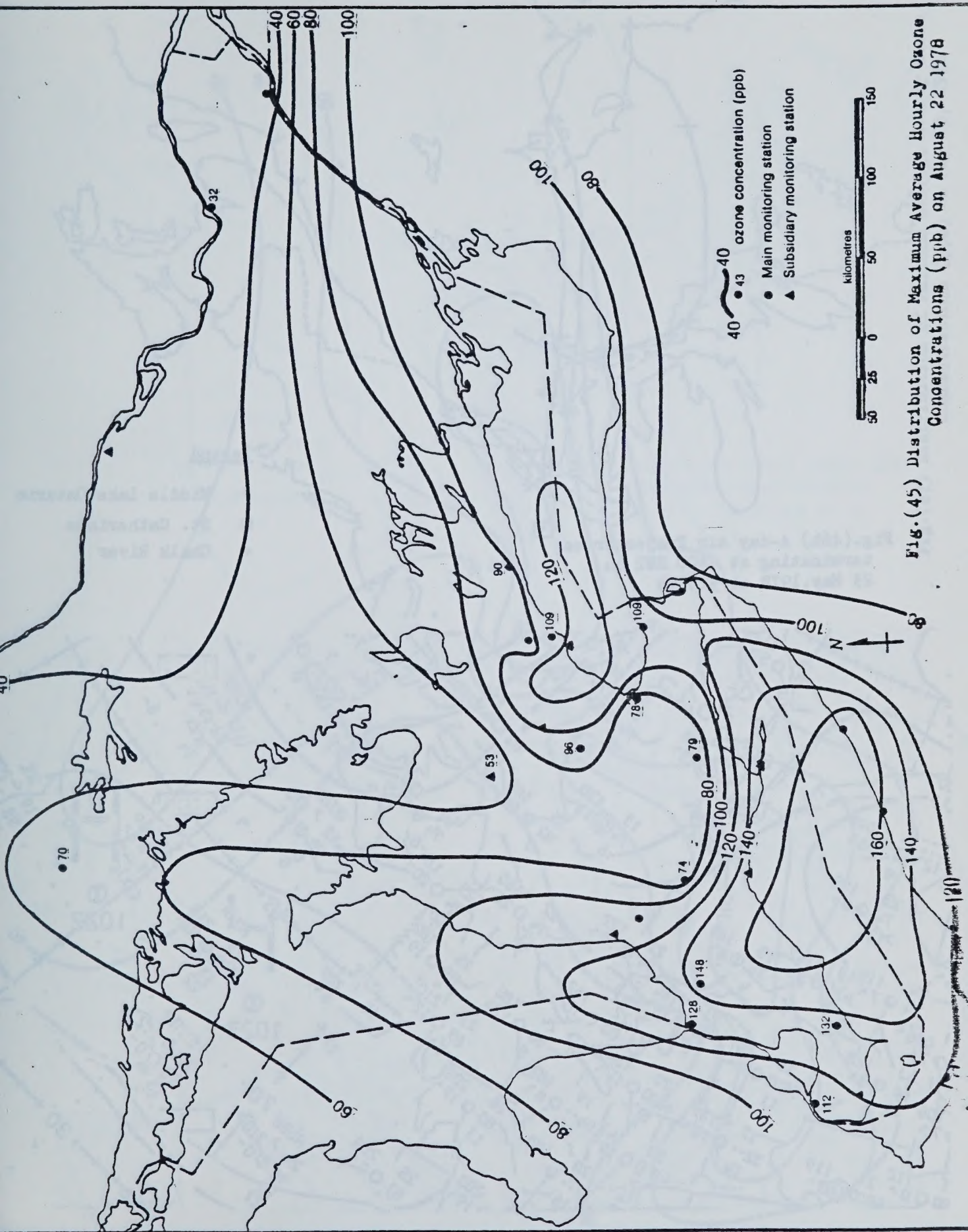


Fig.(45) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on August 22 1978

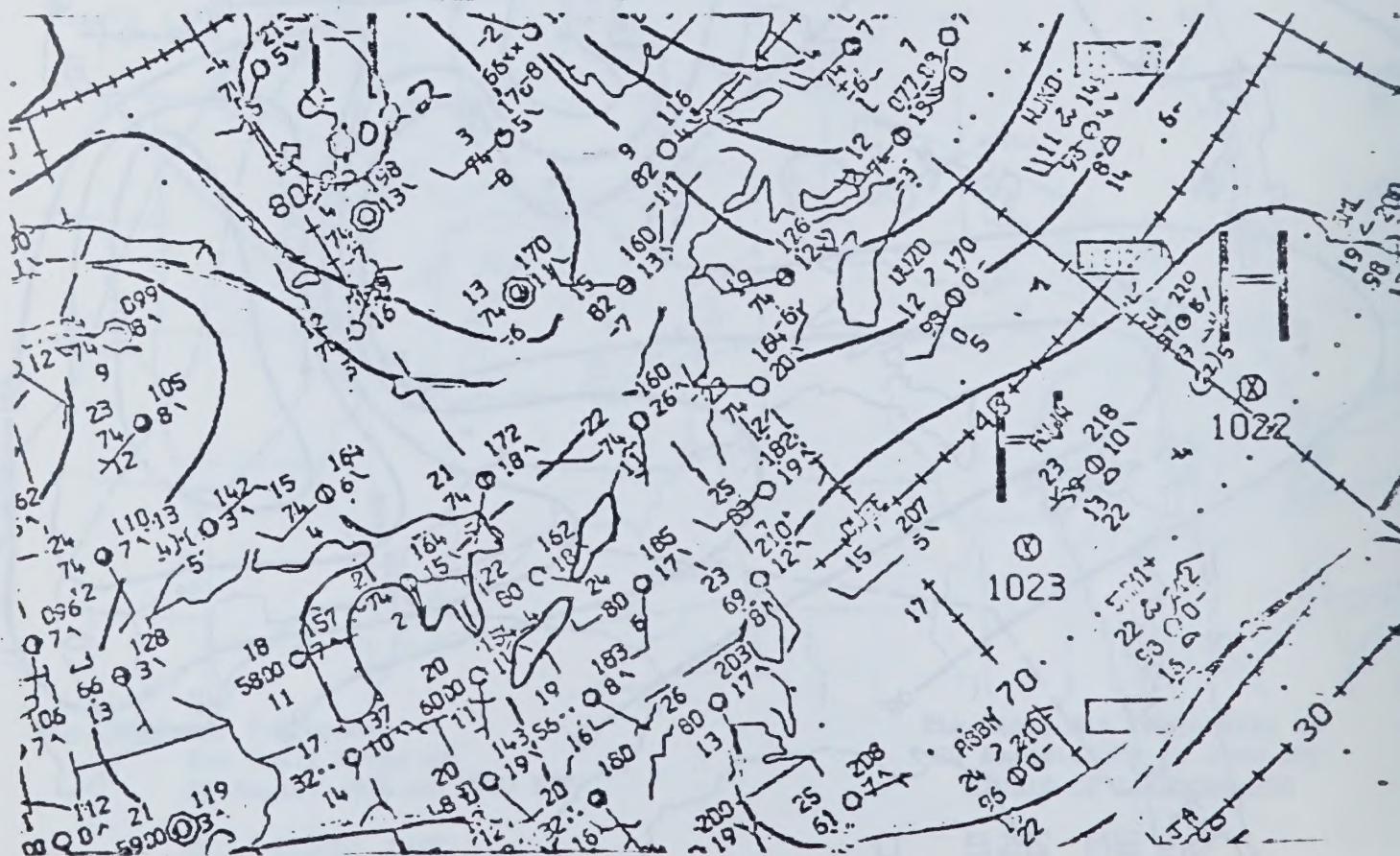
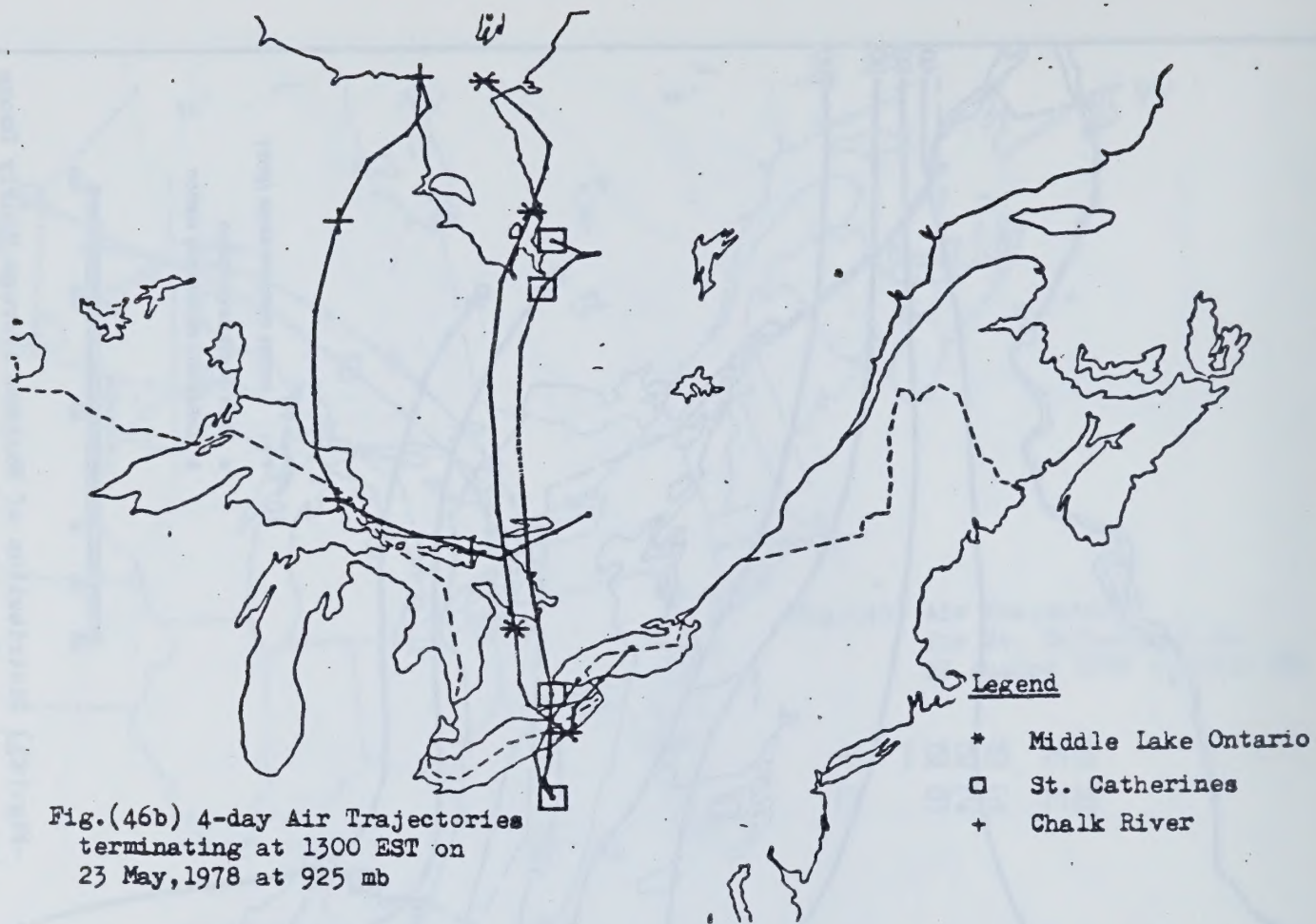


Fig.(46a) Surface Synoptic Weather Map at 1300 EST on May 23, 1978

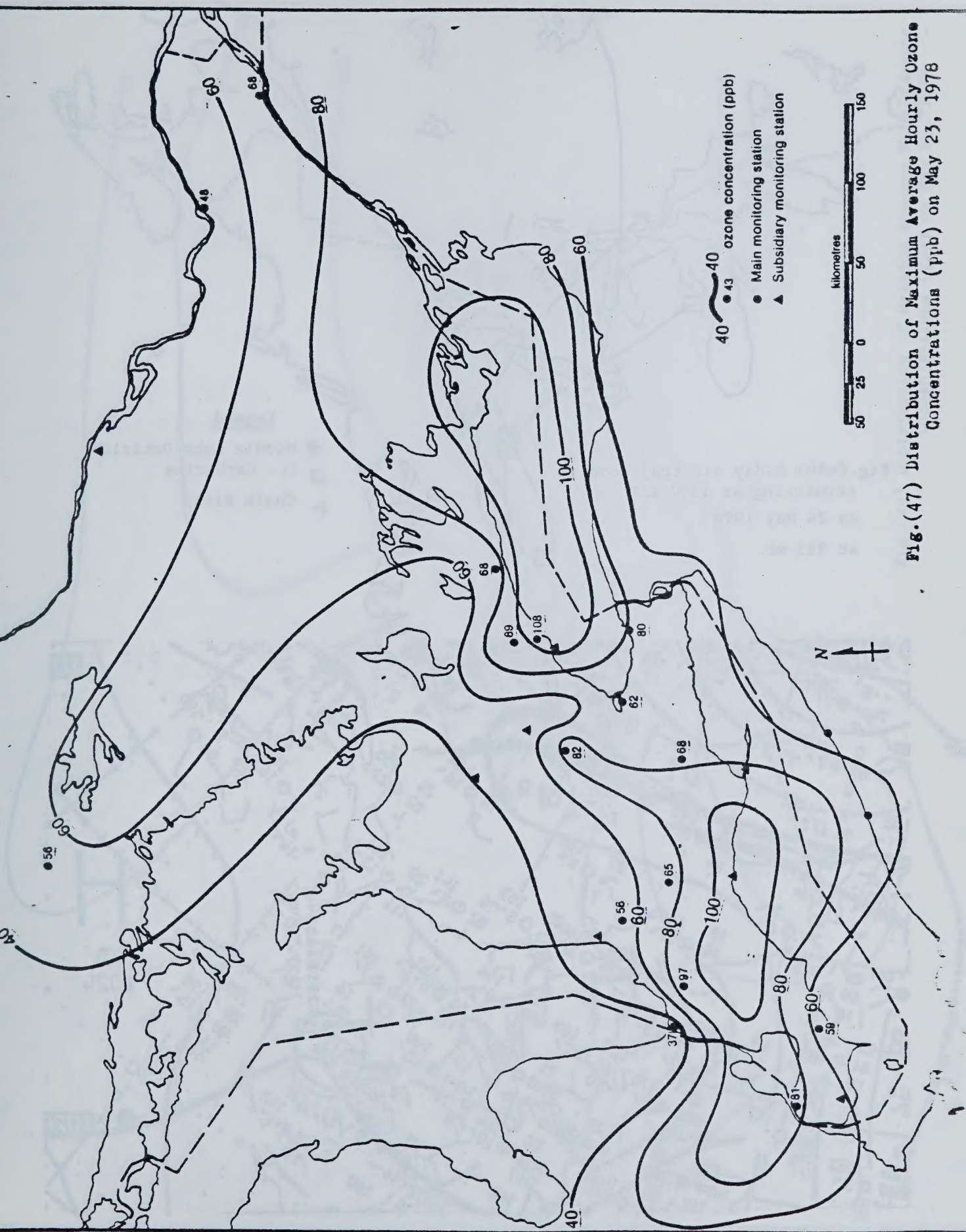


Fig.(47) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on May 23, 1978

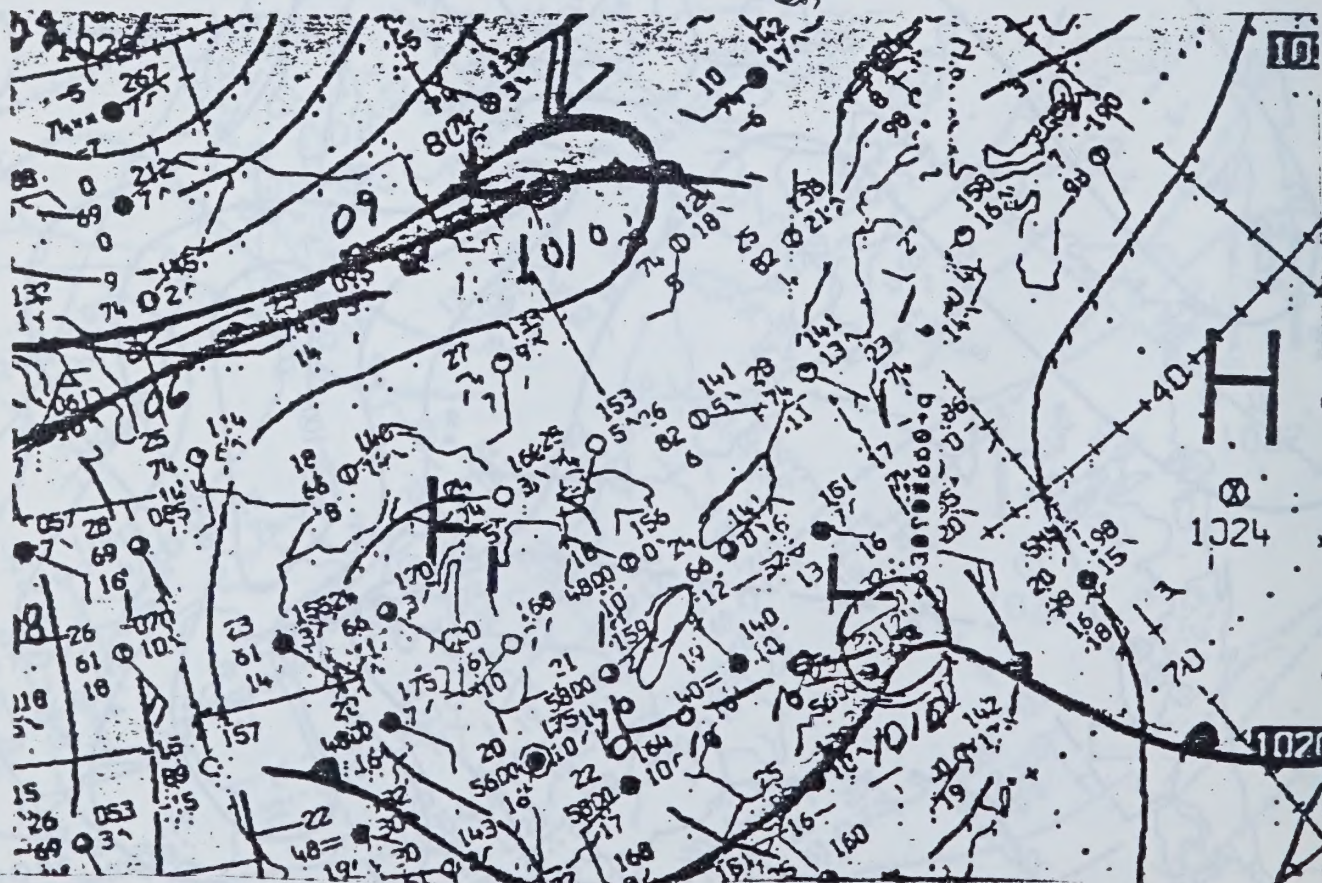
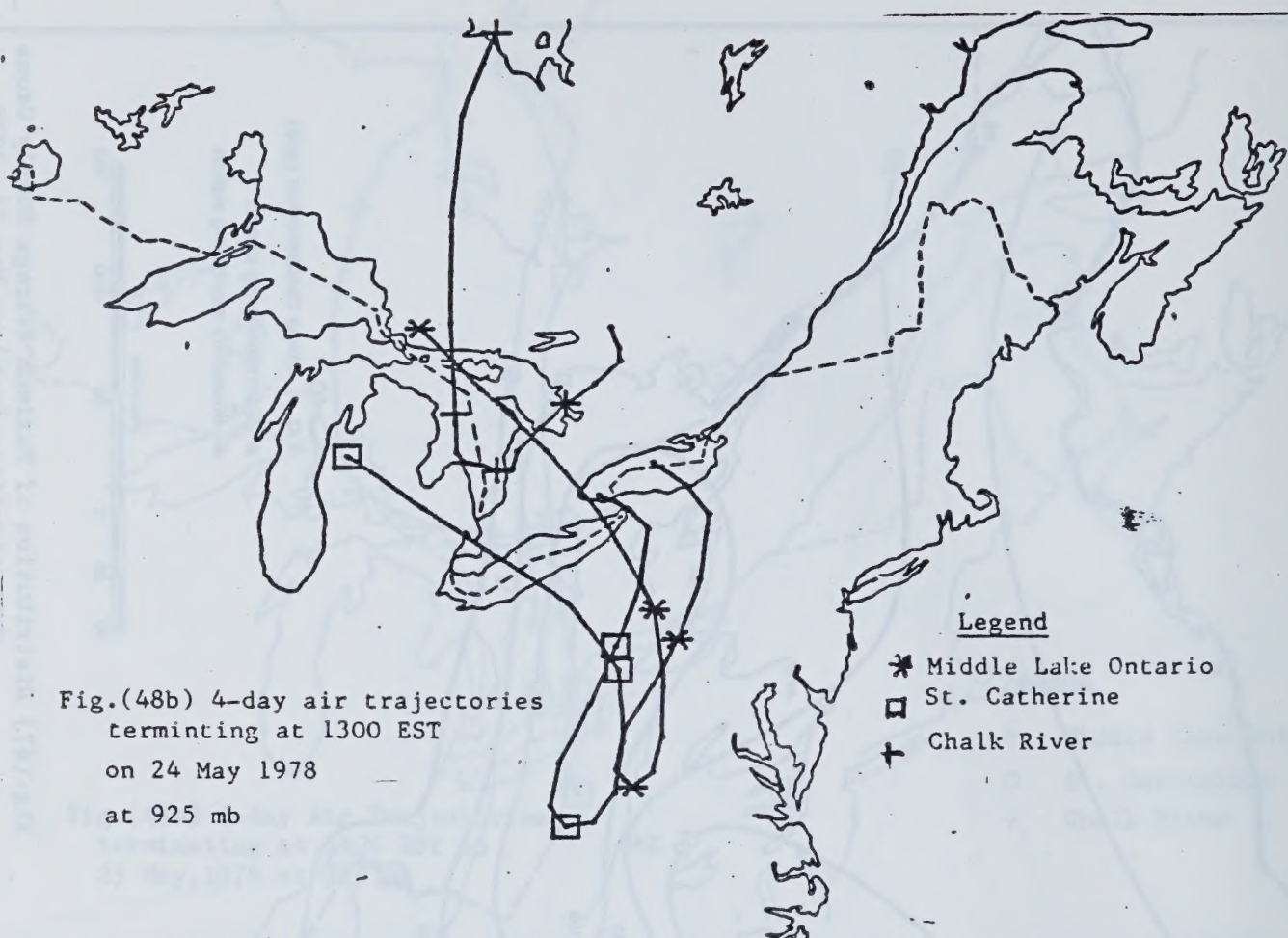


Fig.(48a) Surface Synoptic Weather Map at 1300 EST on May 24, 1978

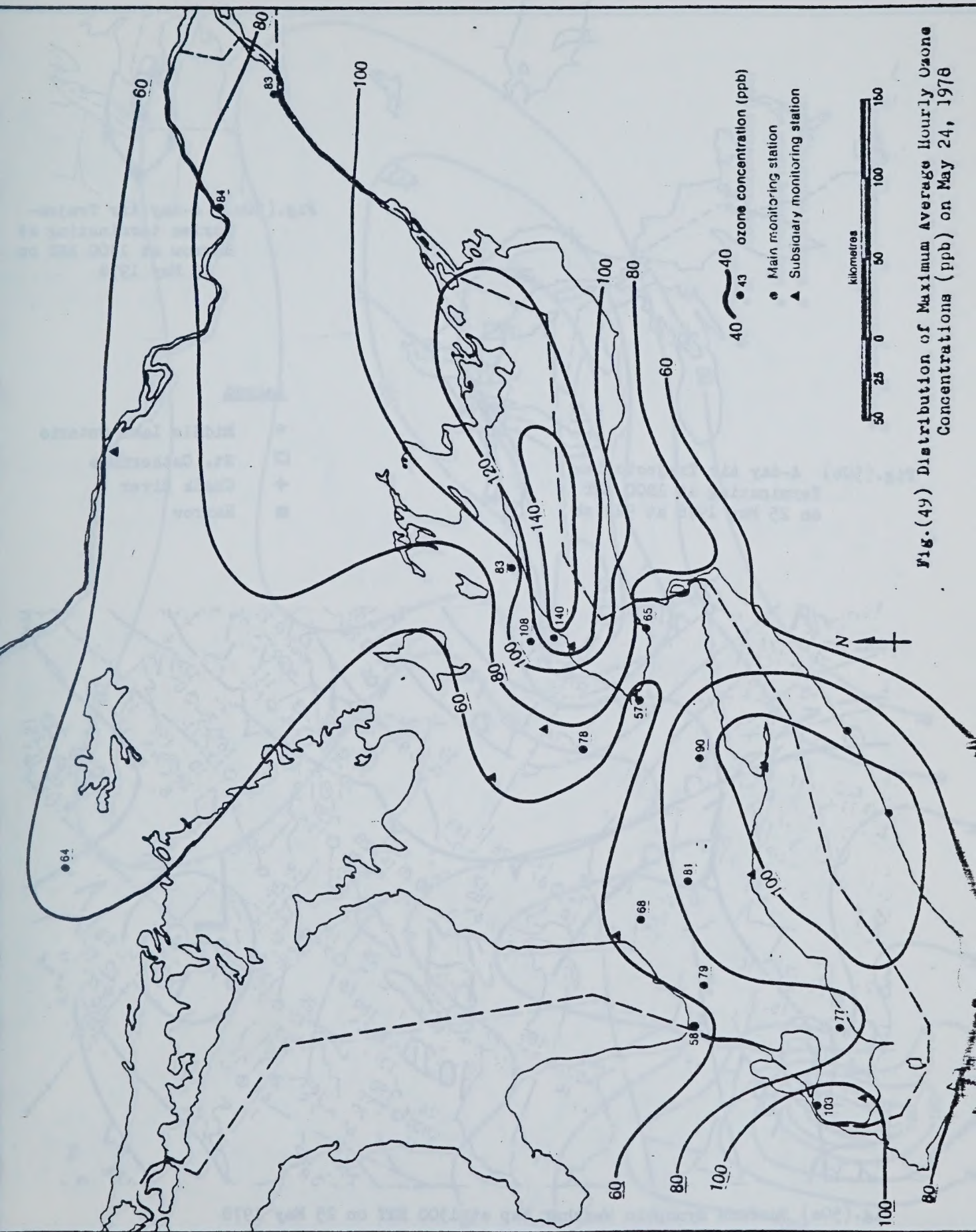


Fig. (49) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on May 24, 1978

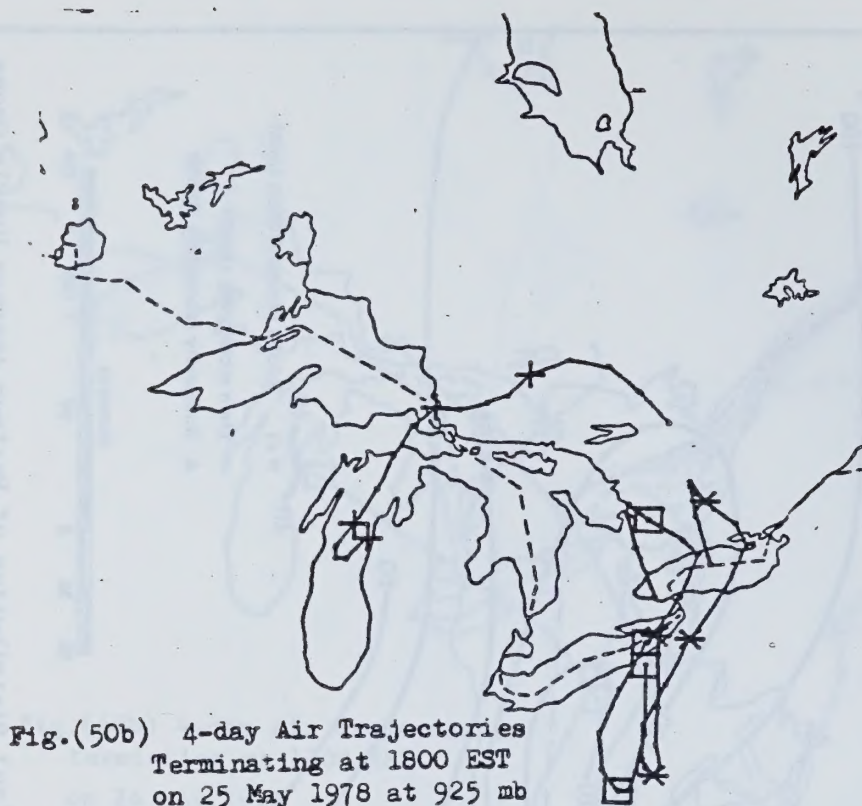


Fig.(50b) 4-day Air Trajectories
Terminating at 1800 EST
on 25 May 1978 at 925 mb



Fig.(50c) 4-day Air Trajec-
tories terminating at
Harrow at 1300 EST on
25 May 1978

Legend

- * Middle Lake Ontario
- St. Catharines
- + Chalk River
- Harrow

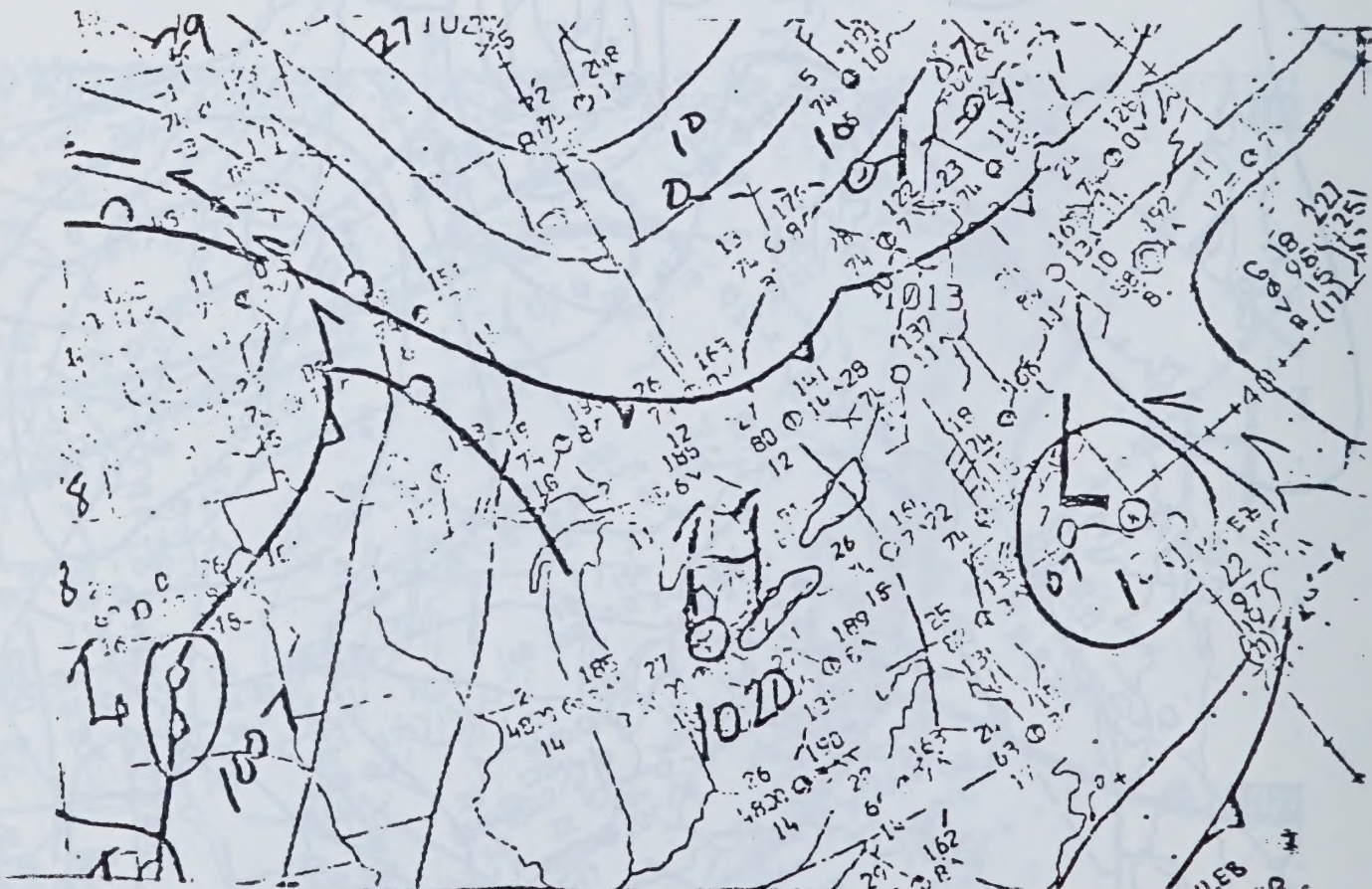


Fig.(50a) Surface Synoptic Weather Map at 1300 EST on 25 May 1978

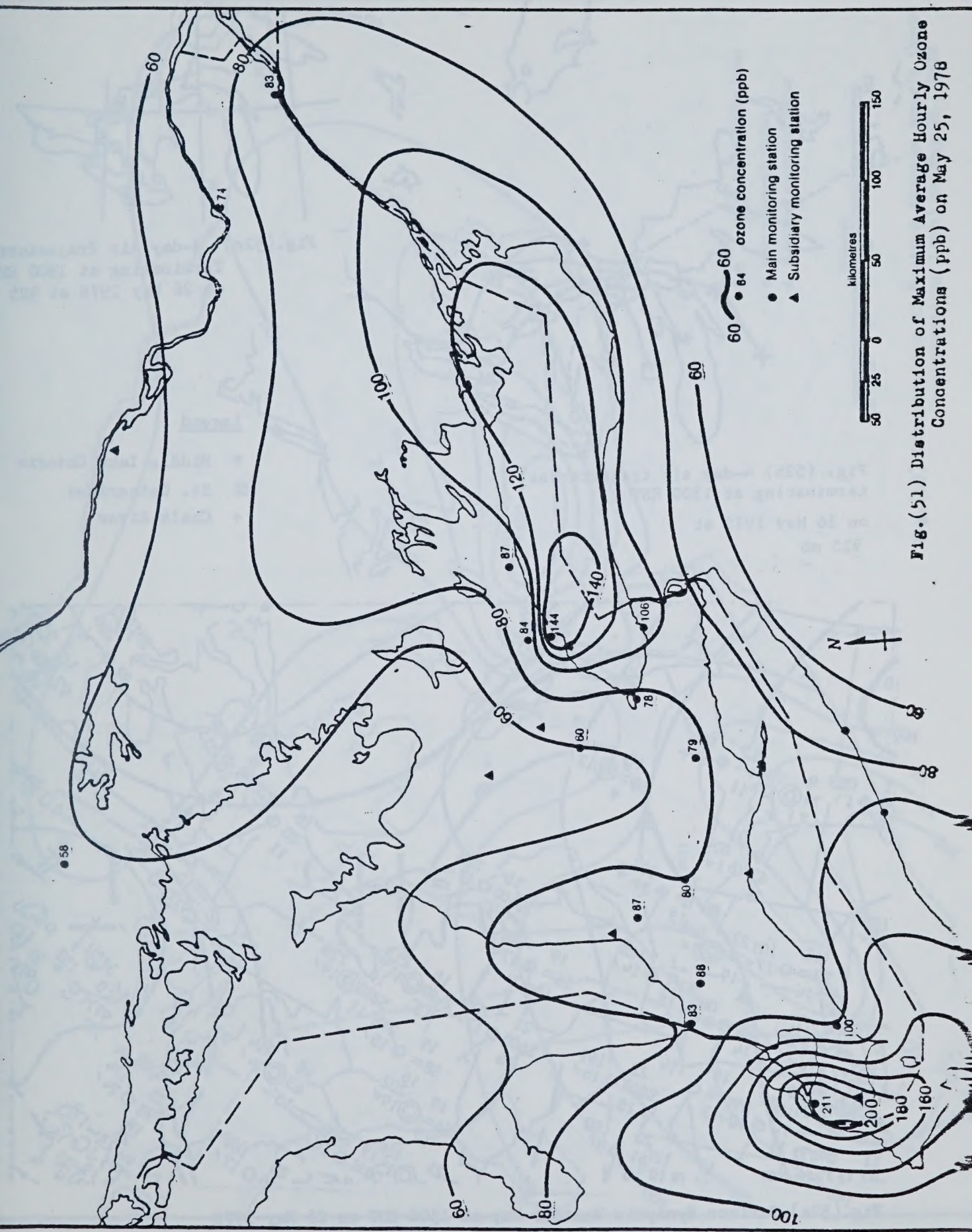


Fig.(51) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on May 25, 1978

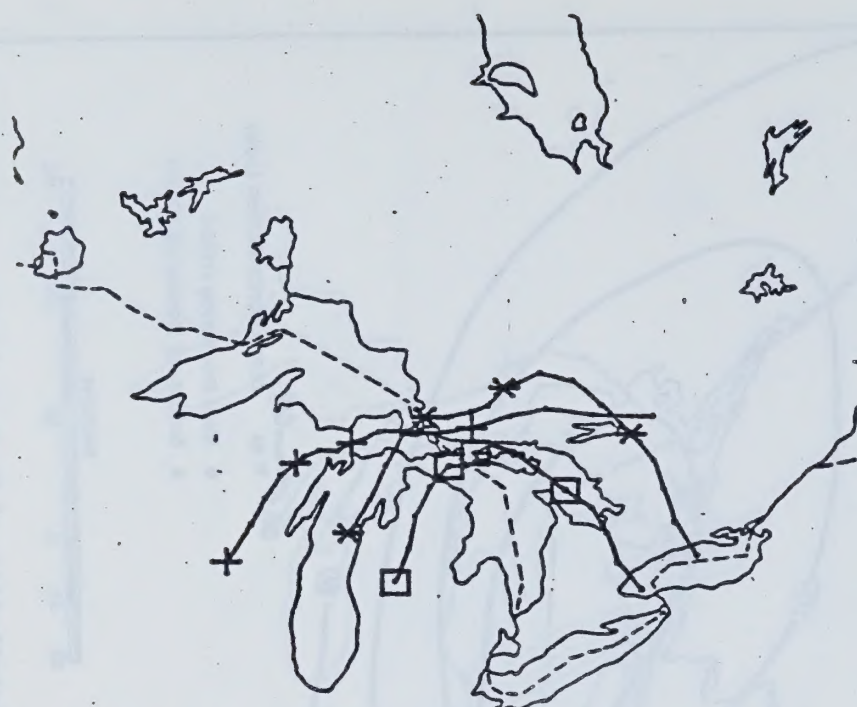


Fig.. (52b) 4-day air trajectories
terminating at 1300 EST
on 26 May 1978 at
925 mb

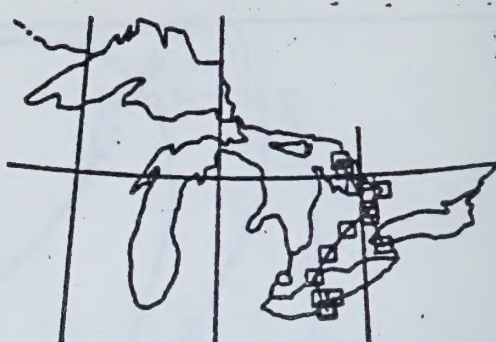


Fig.(52c) 4-day Air Trajectories
Terminating at 1900 EST
on 26 May 1978 at 925 mb

Legend

- * Middle Lake Ontario
- St. Catherines
- + Chalk River

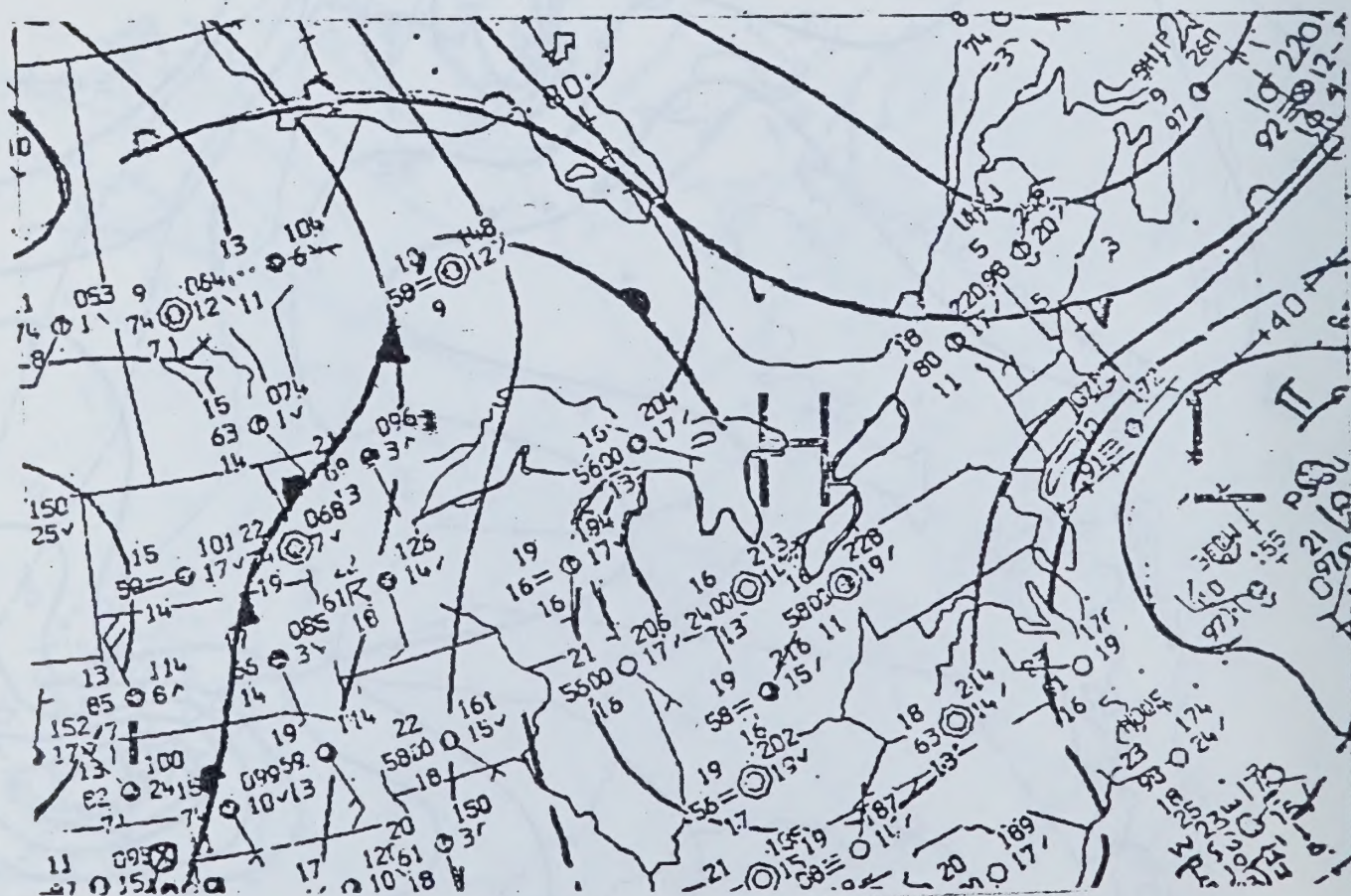


Fig.(52a) Surface Synoptic Weather Map at 1300 EST on 26 May 1978

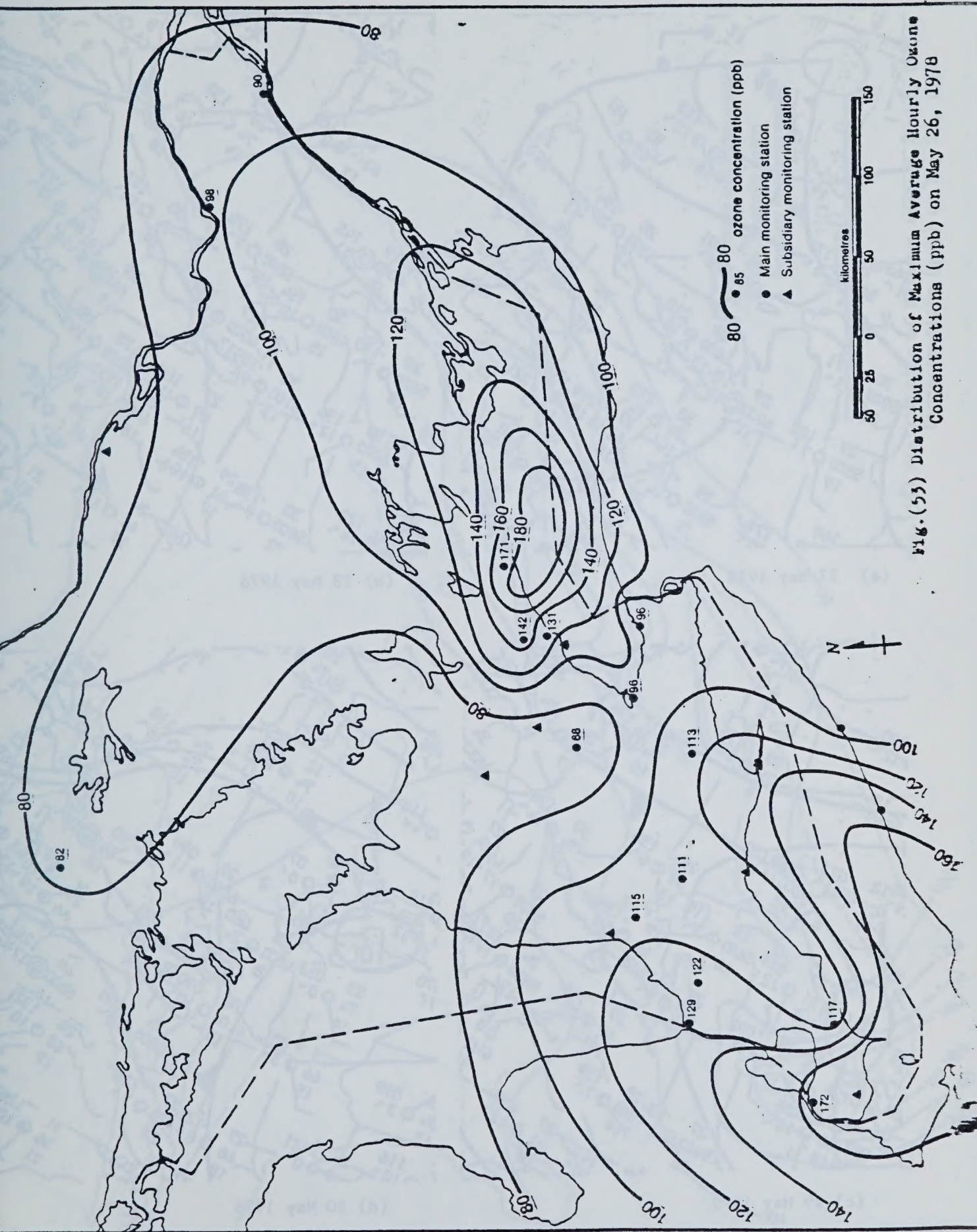
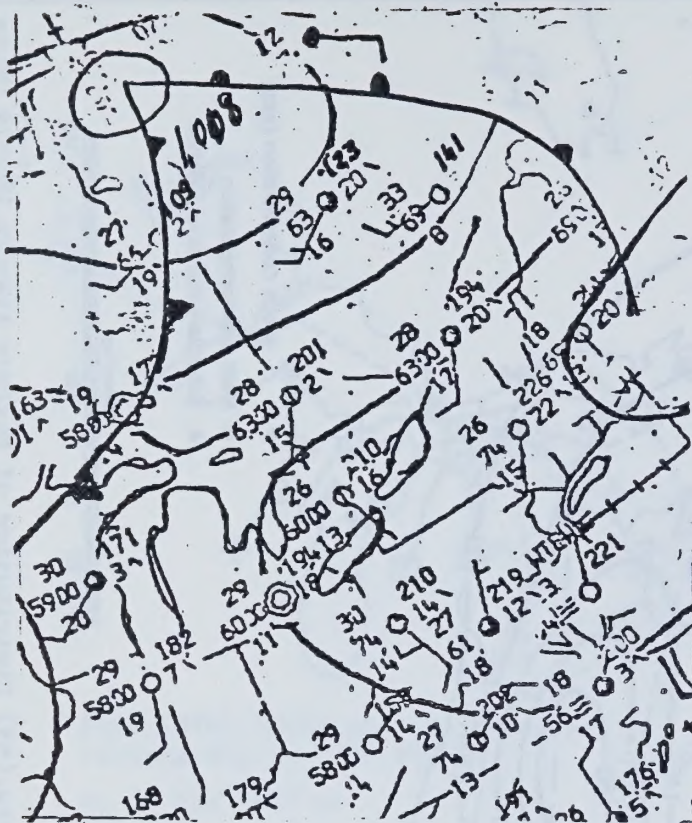
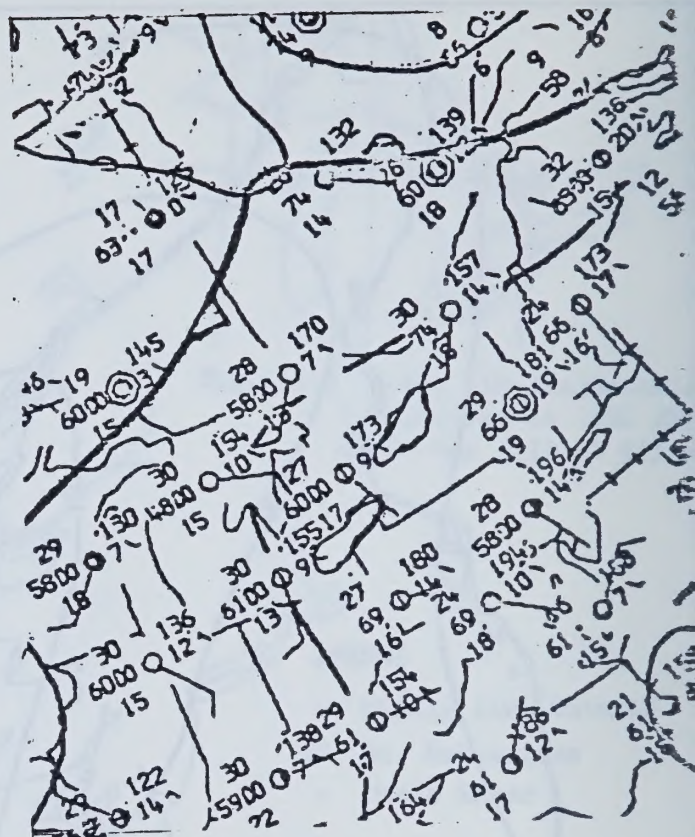


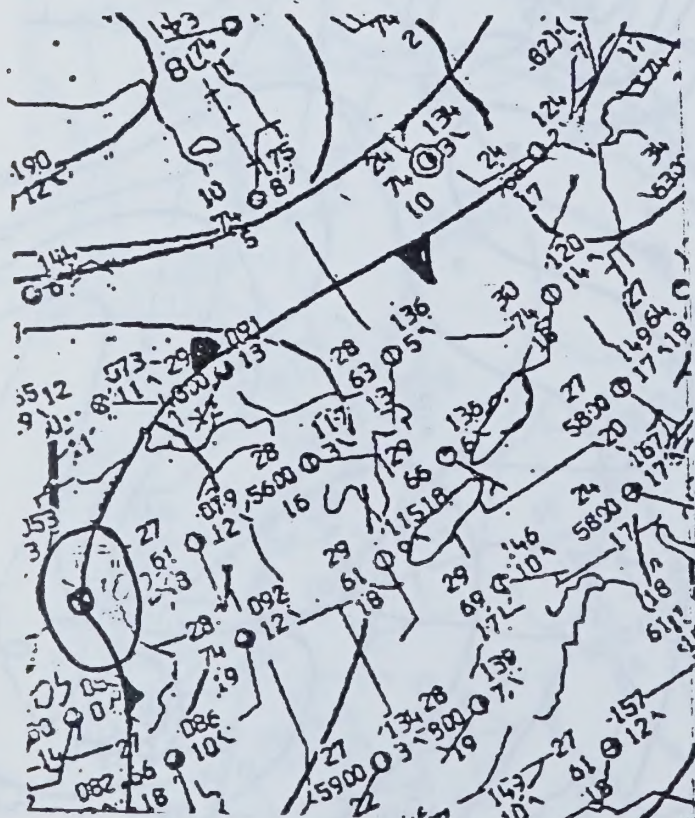
Fig. (53) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on May 26, 1978



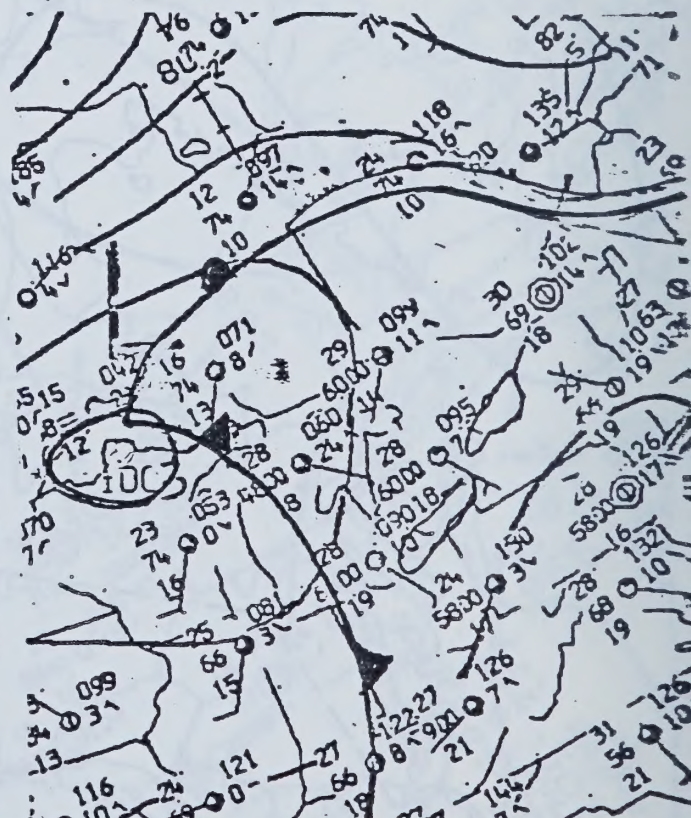
(a) 27 May 1978



(b) 23 May 1978



(c) 29 May 1978



(d) 30 May 1978

fig. (54) Surface synoptic weather map at 1300 EST

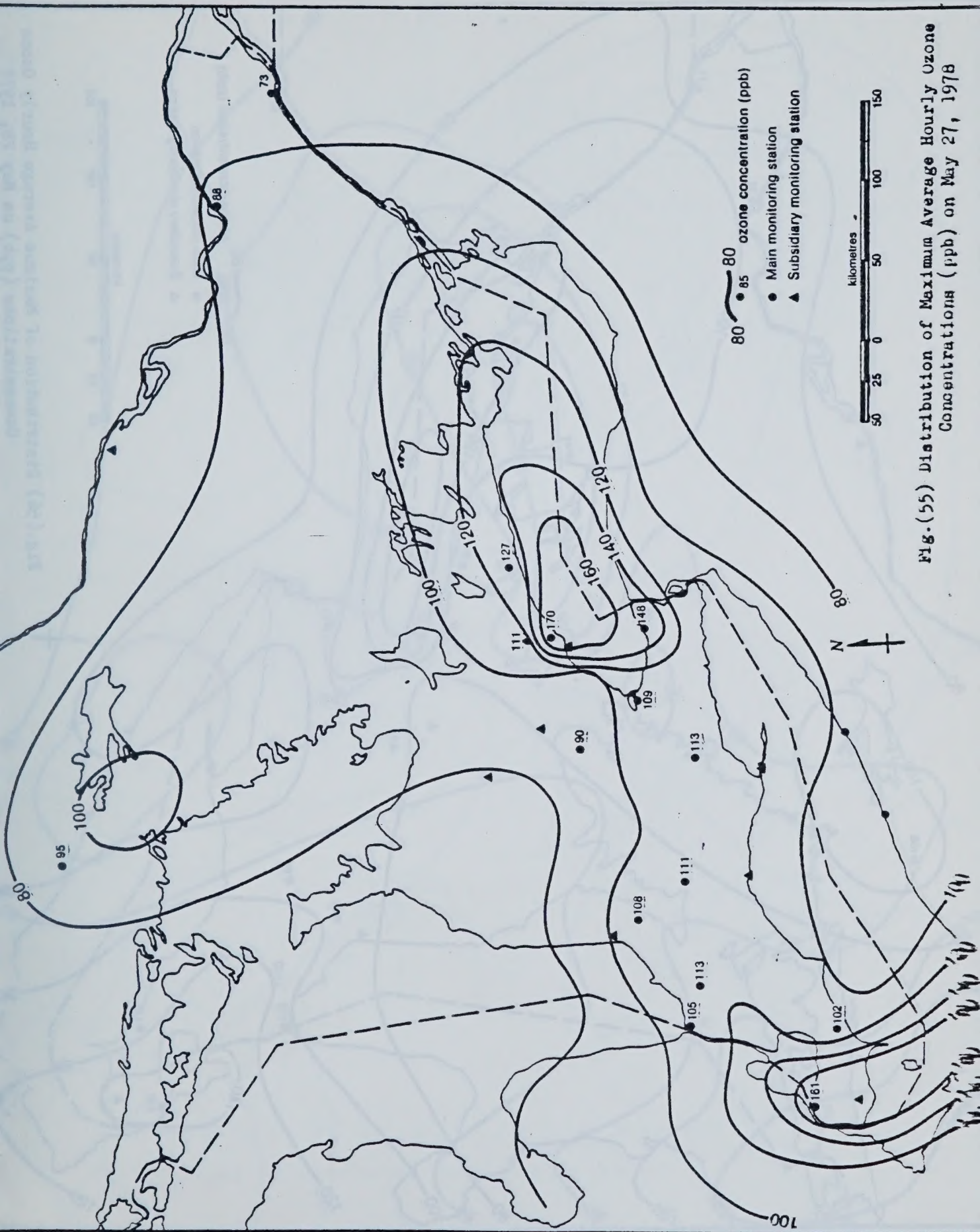


Fig.(55) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on May 27, 1978

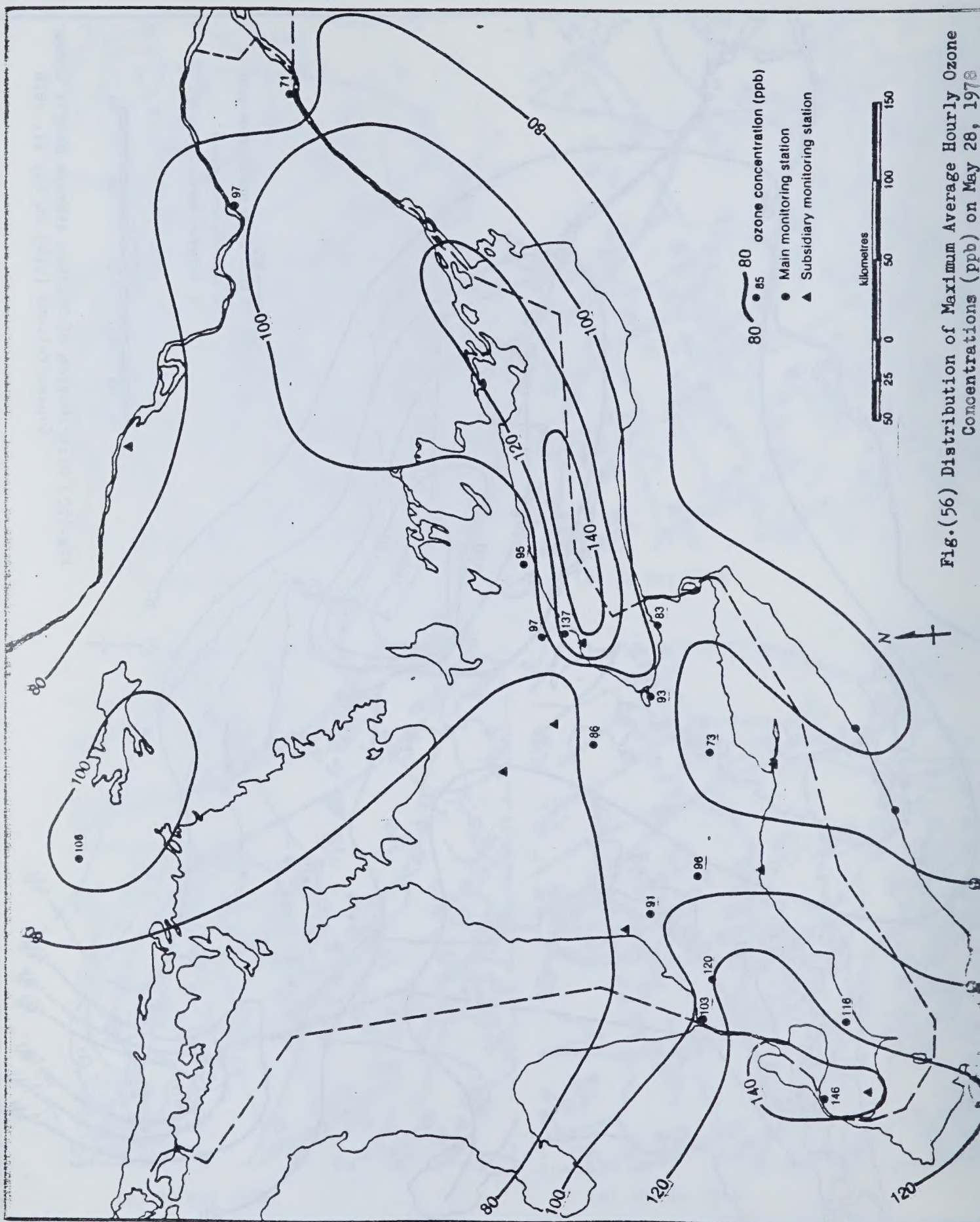


Fig.(56) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on May 28, 1978

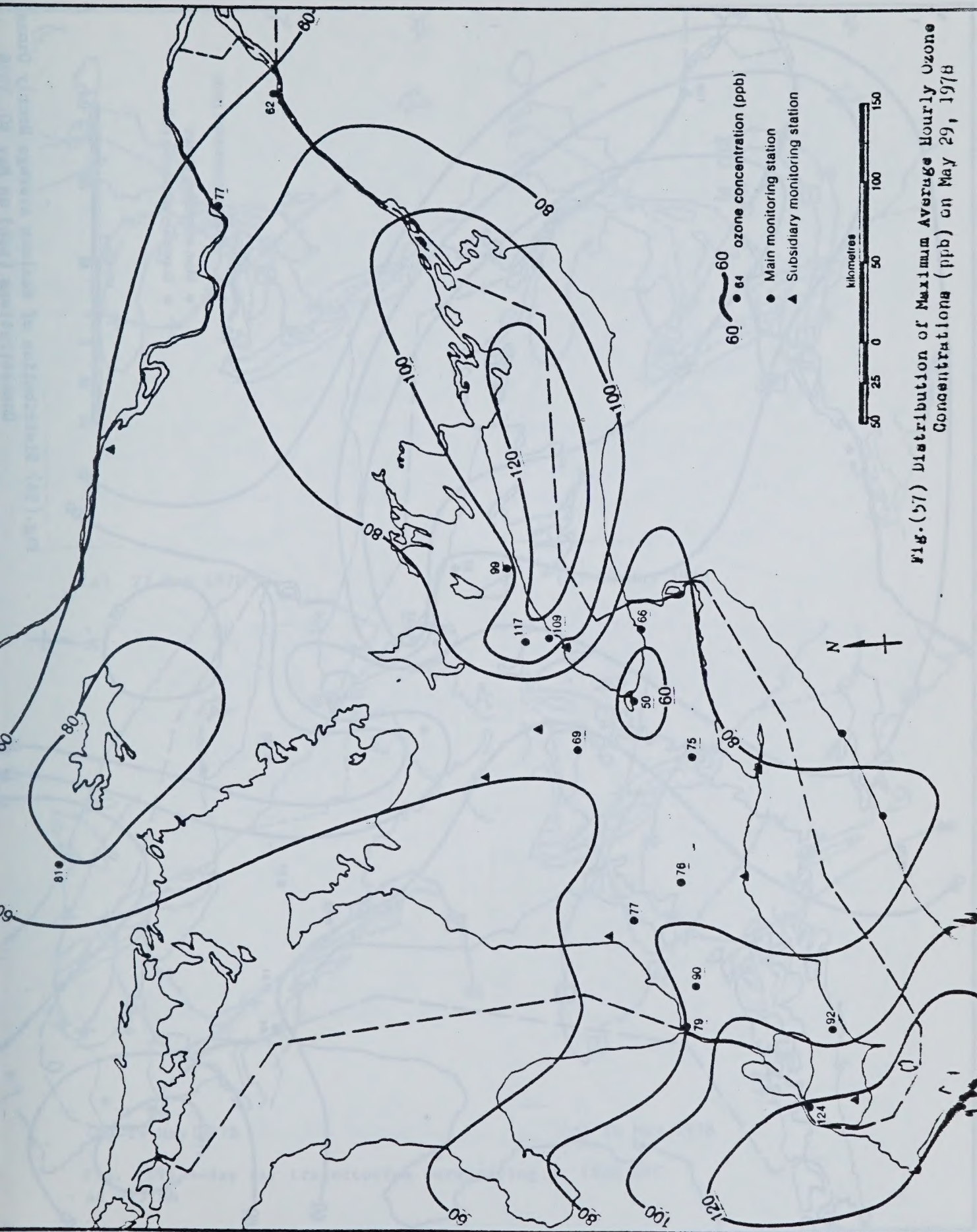


Fig.(57) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on May 29, 1978

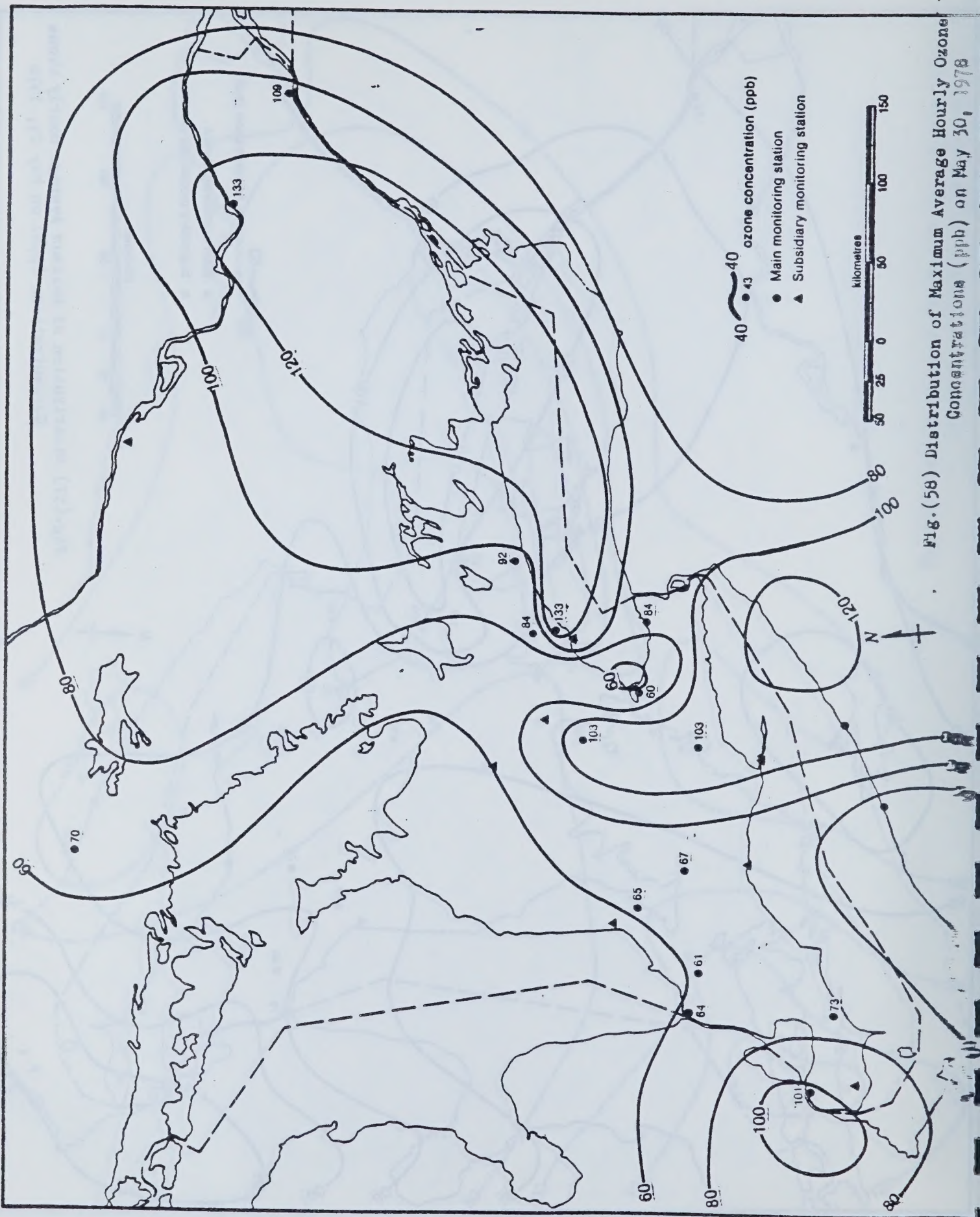
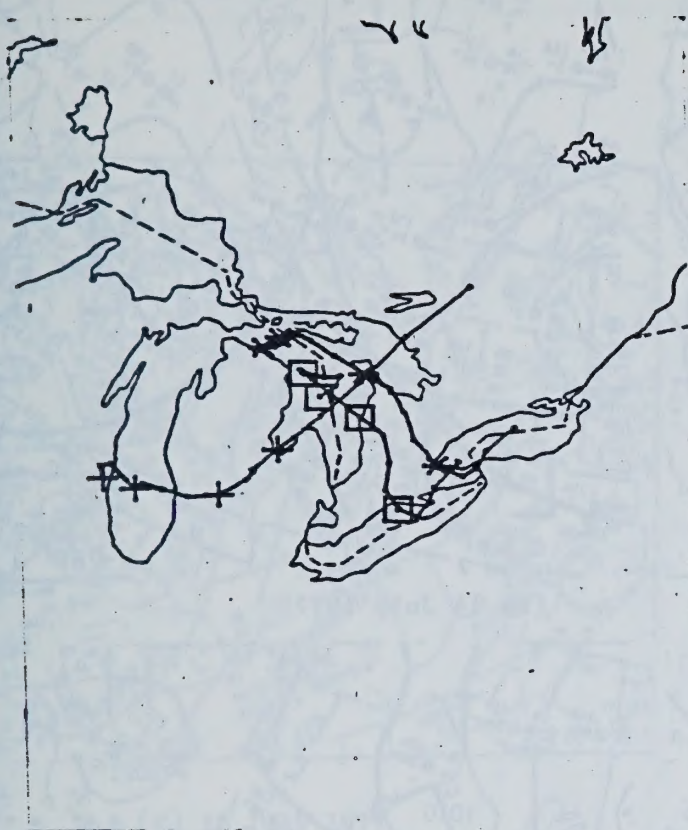
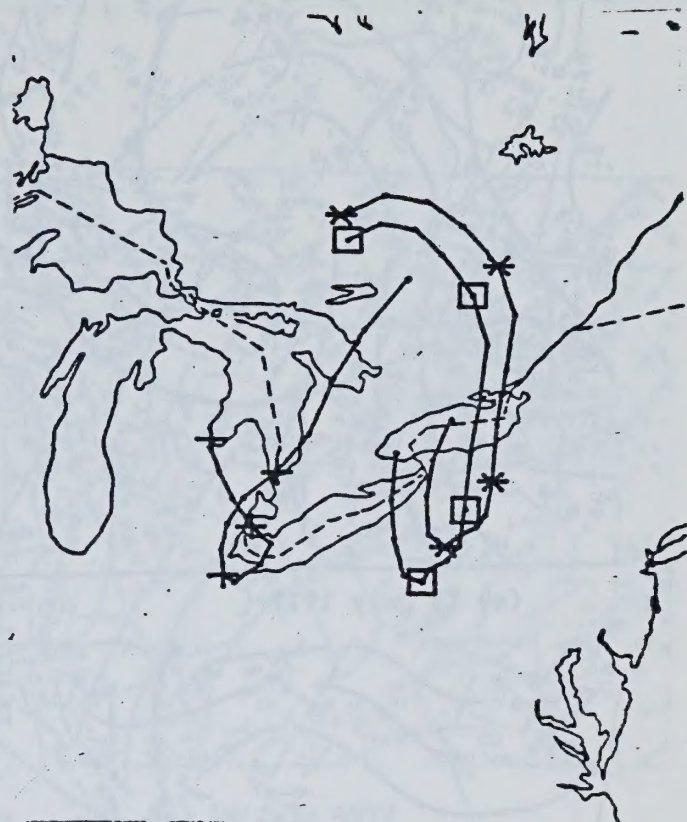


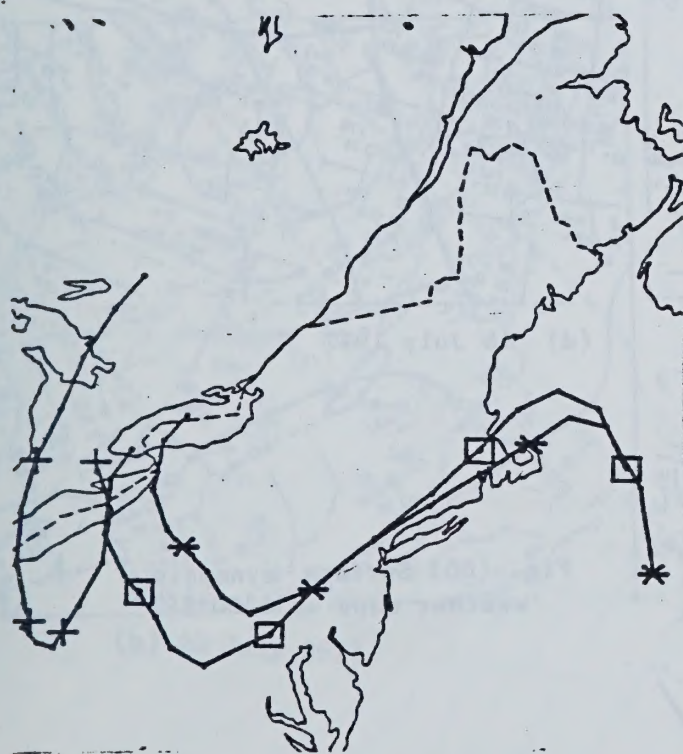
Fig. (58) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on May 30, 1978



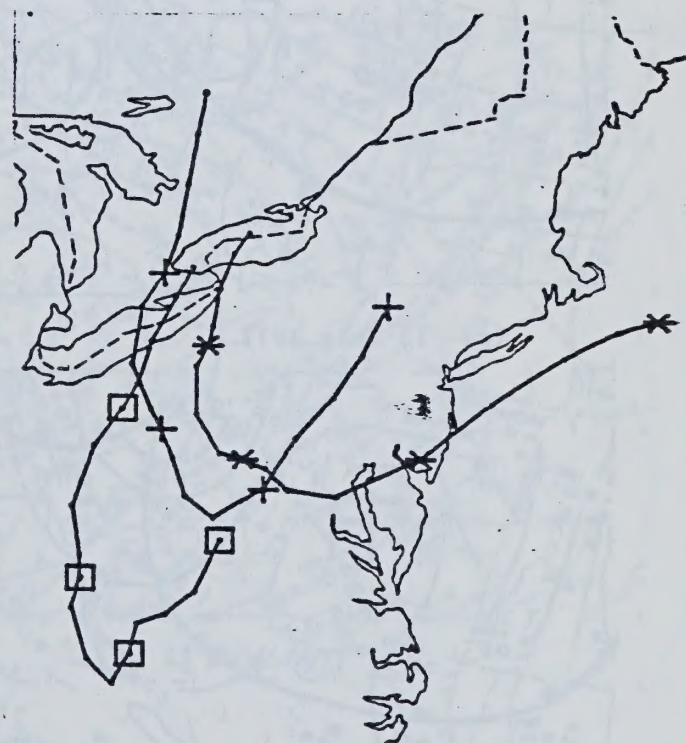
(a) 27 May 1978



(b) 28 May 1978



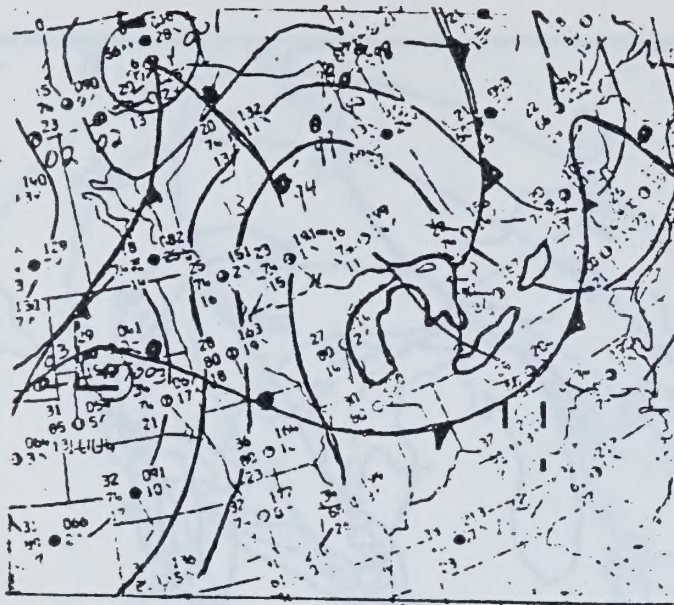
(c) 29 May 1978



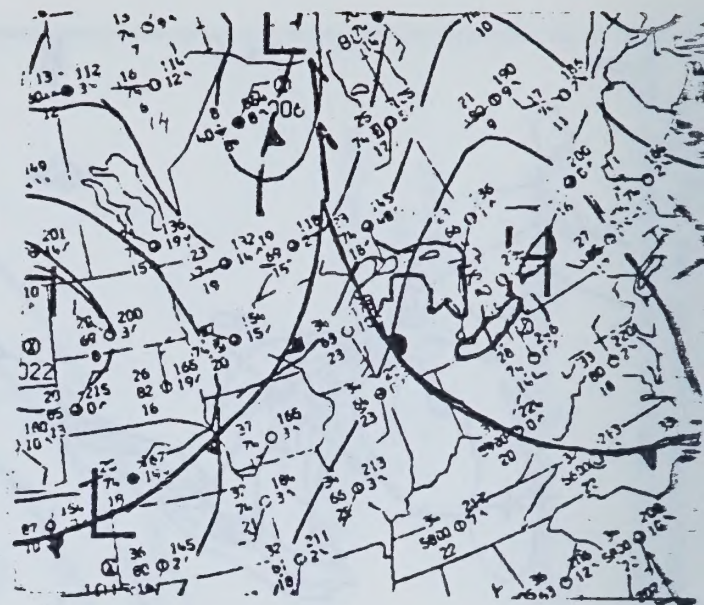
(d) 30 May 1978

Fig. (59) 4-day air trajectories terminating at 1300 EST
at 925 mb

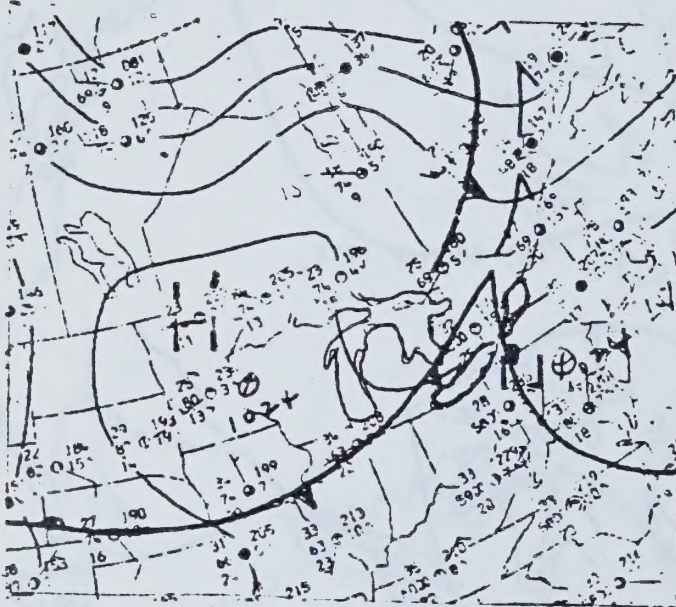
Legend: * Middle Lake Ontario, □ St. Catherine, + Chalk River



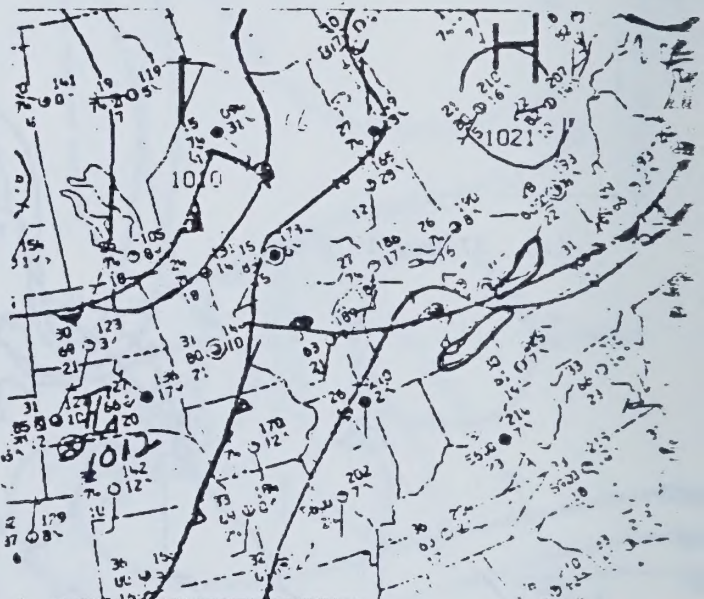
(a) 13 July 1977



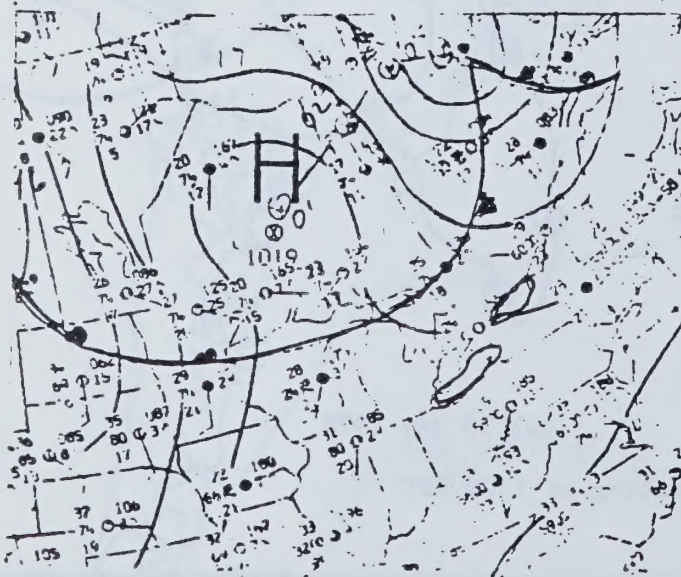
(b) 14 July 1977



(c) 15 July 1977

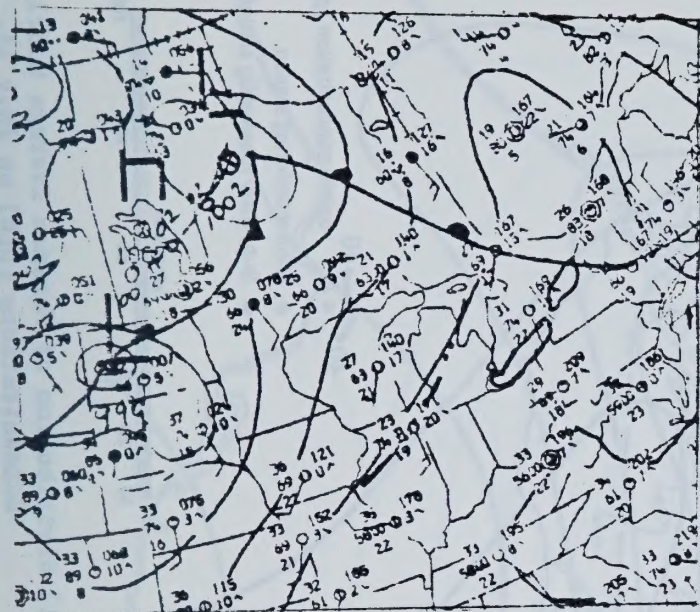


(d) 16 July 1977

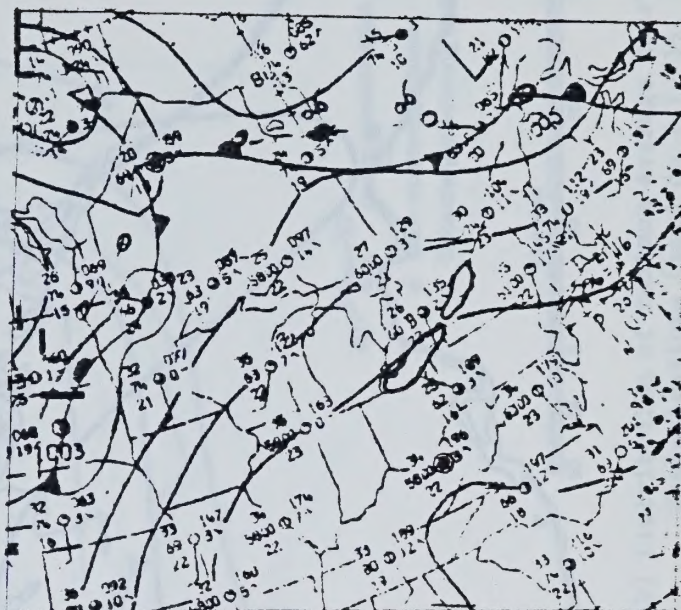


(e) 17 July 1977

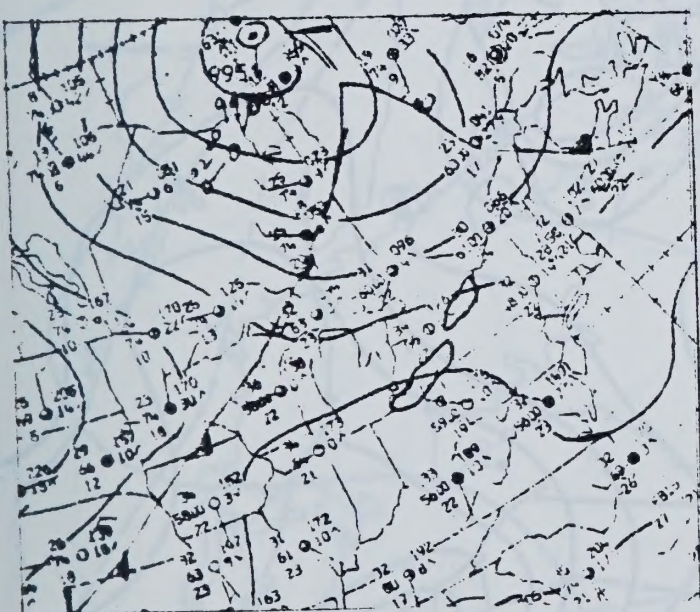
Fig. (60) Surface synoptic weather maps at 1300 EST



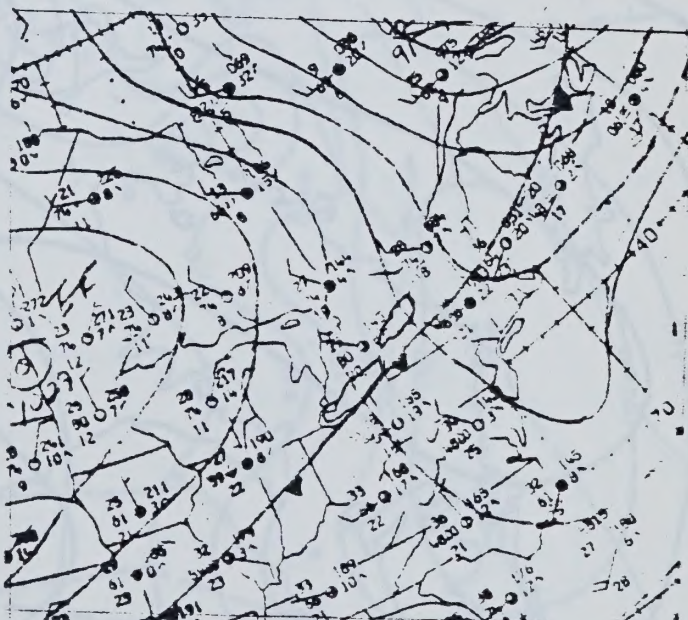
(f) 18 July 1977



(g) 19 July 1977



(h) 20 July 1977



(i) 21 July 1977

Fig.(60) Surface Synoptic Maps at 1300 EST

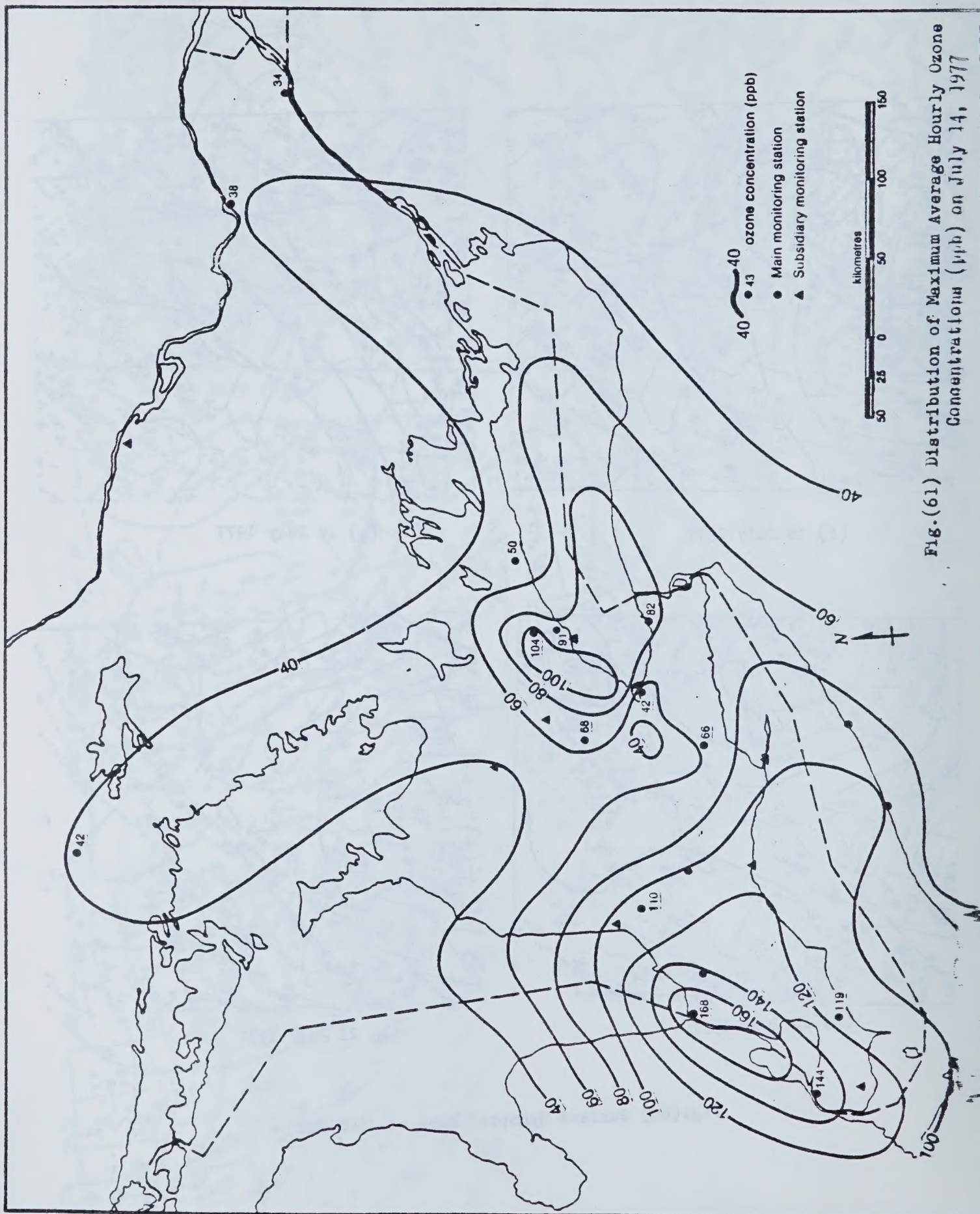


Fig.(61) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on July 14, 1977

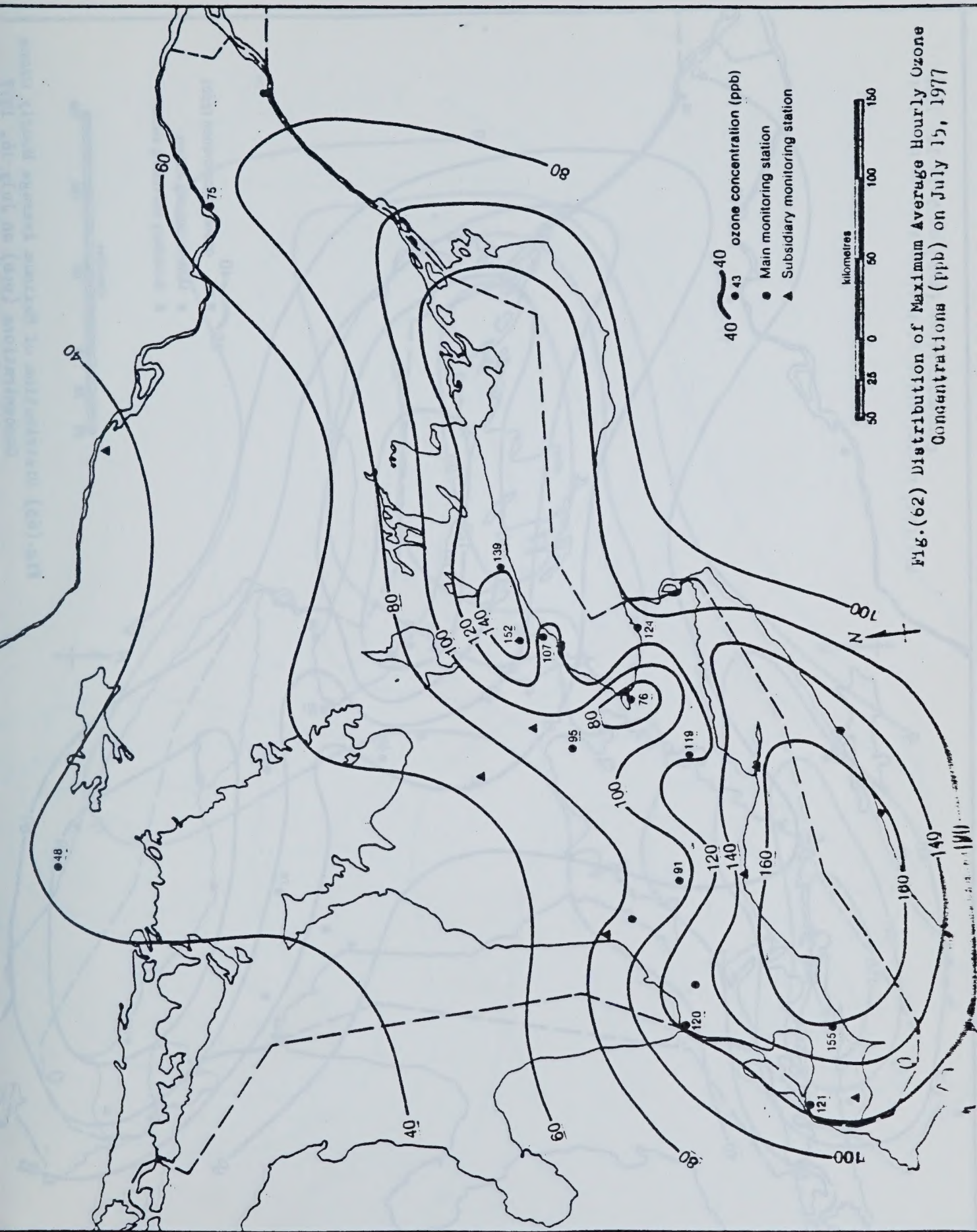


Fig.(62) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on July 15, 1977

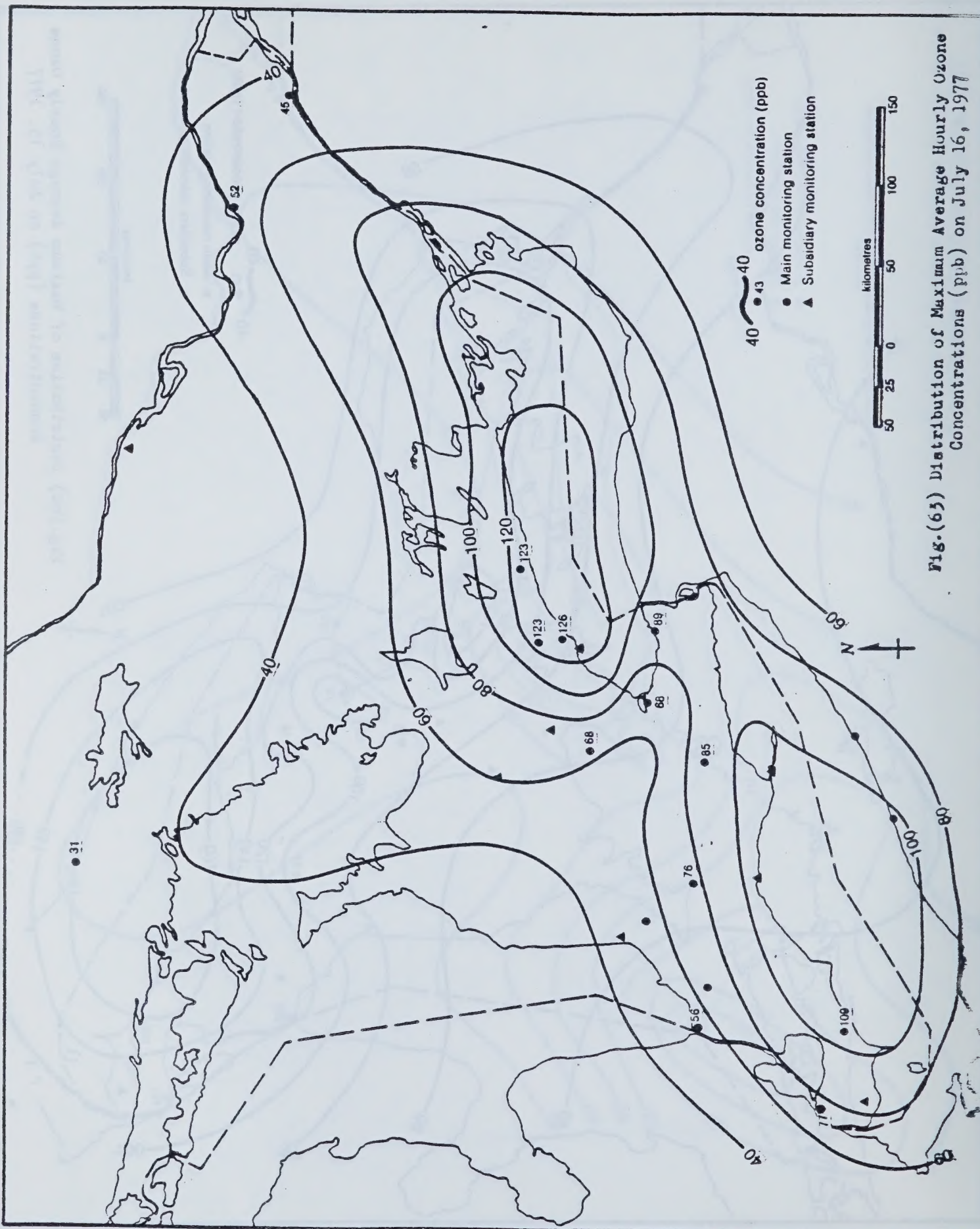


Fig.(65) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on July 16, 1977

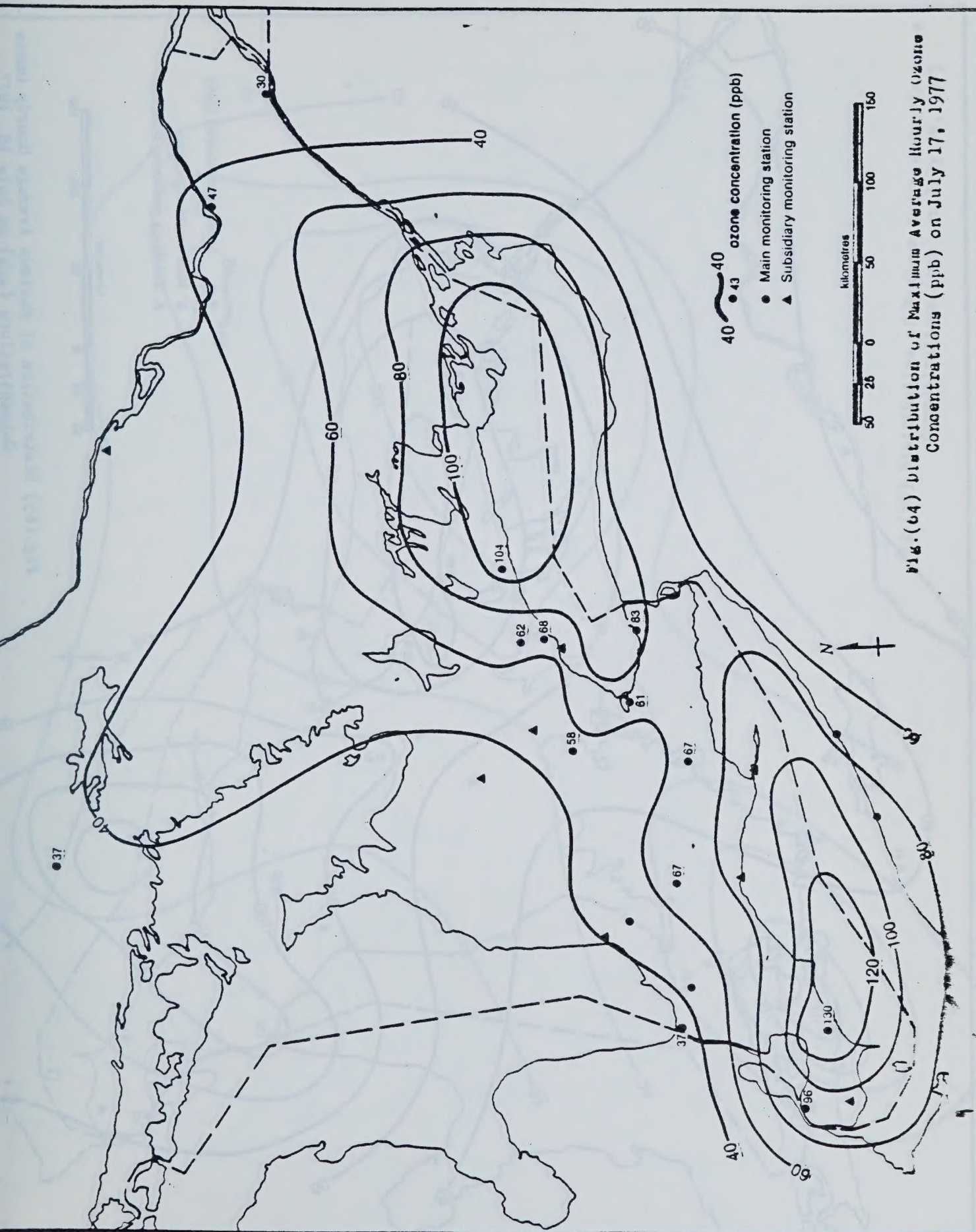


Fig. (64) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on July 17, 1977

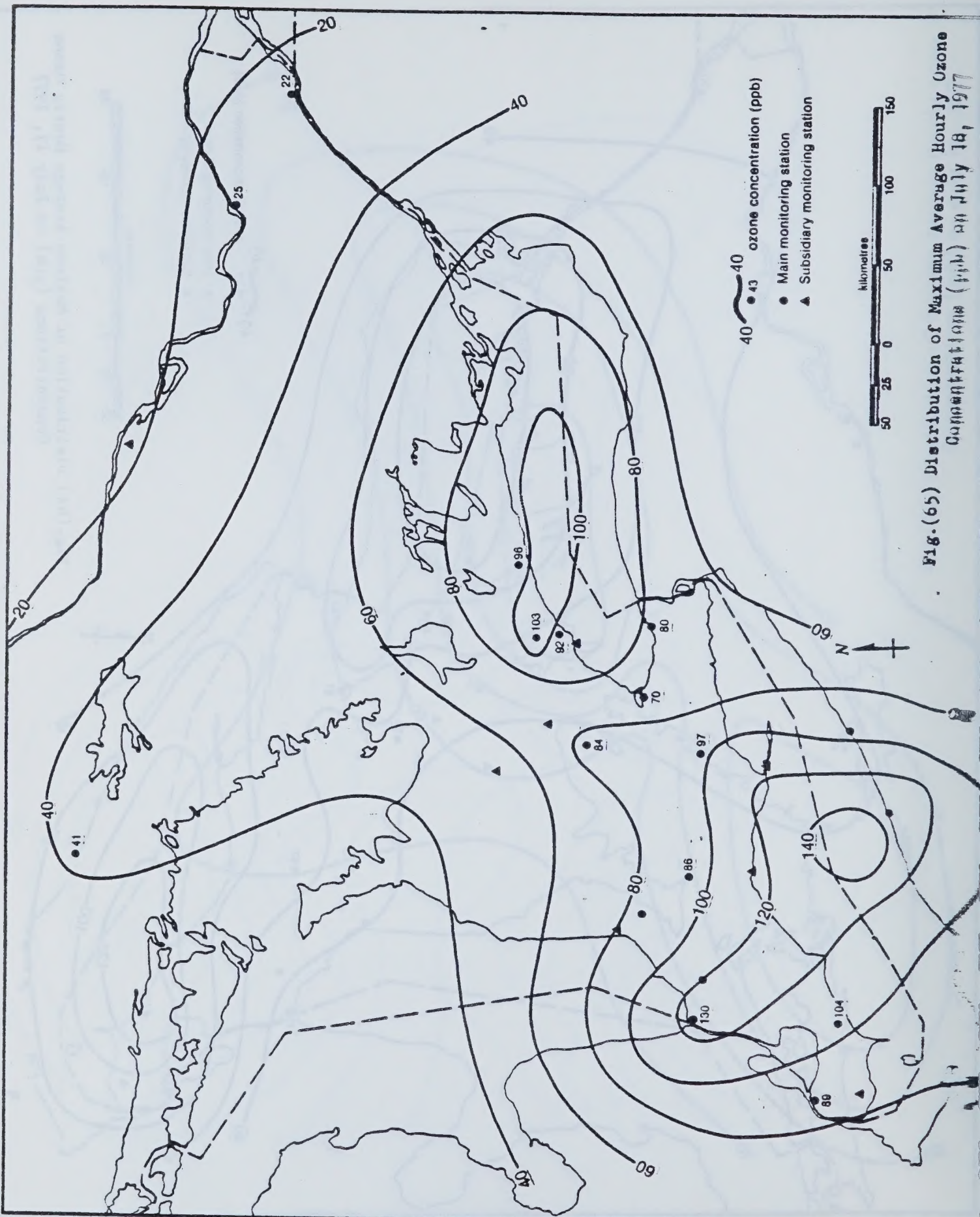


Fig.(65) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on July 18, 1977

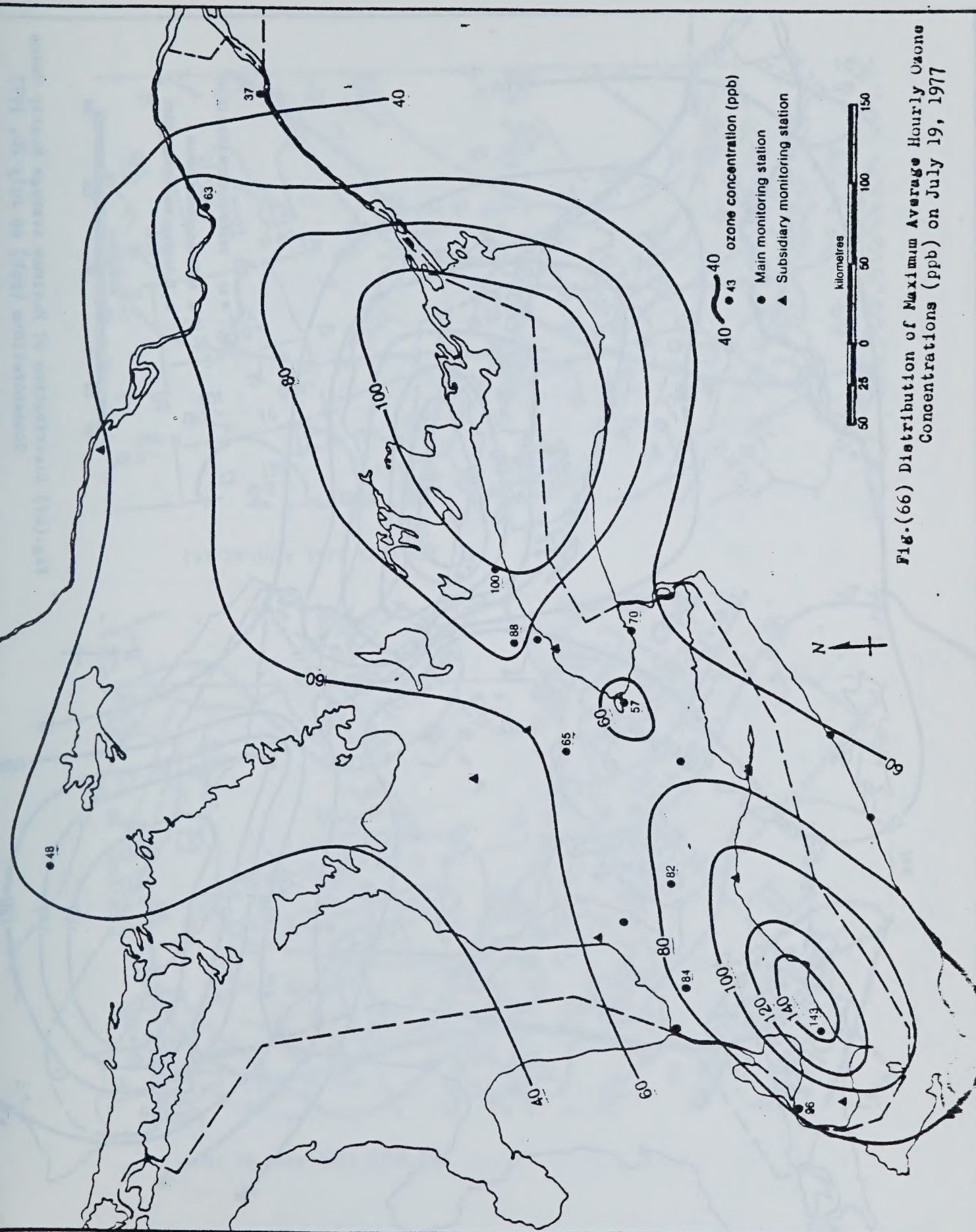


Fig.(66) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on July 19, 1977

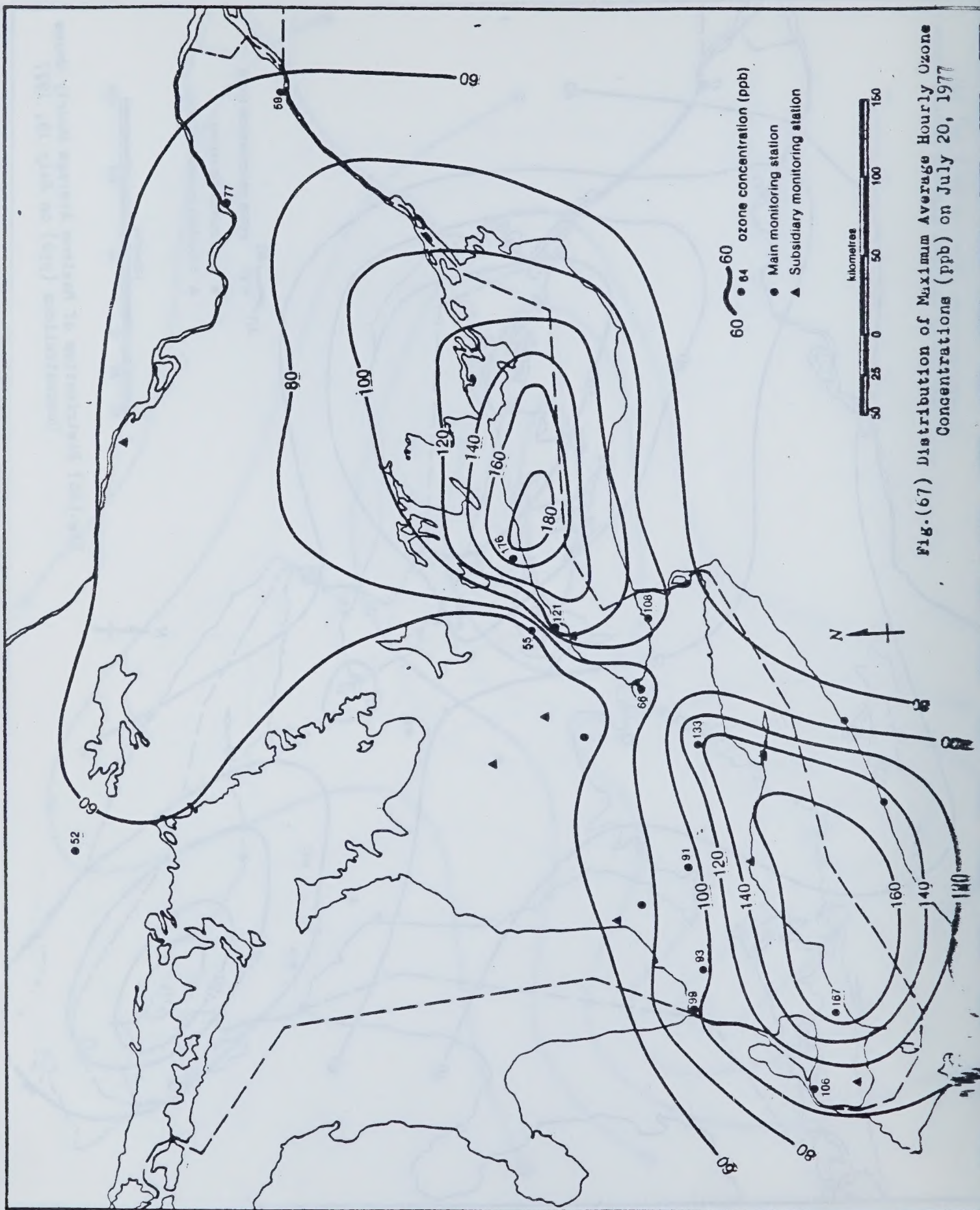
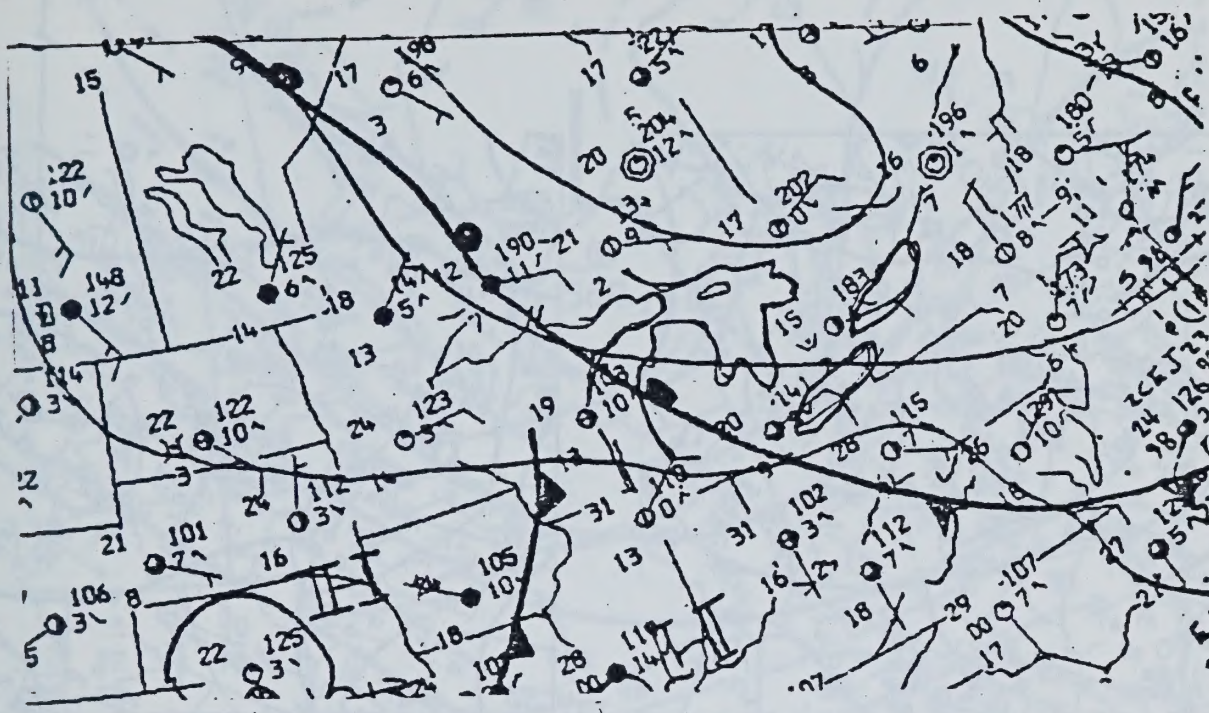
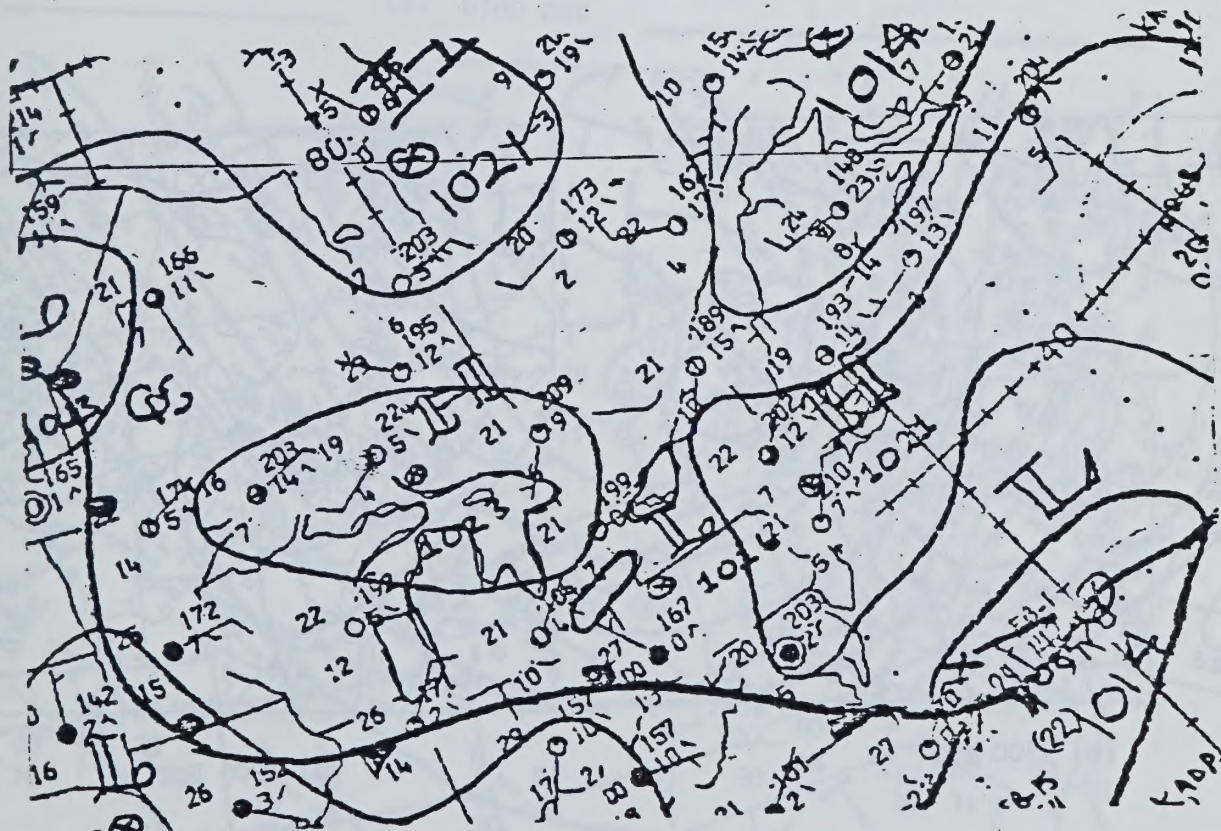


Fig.(67) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on July 20, 1977

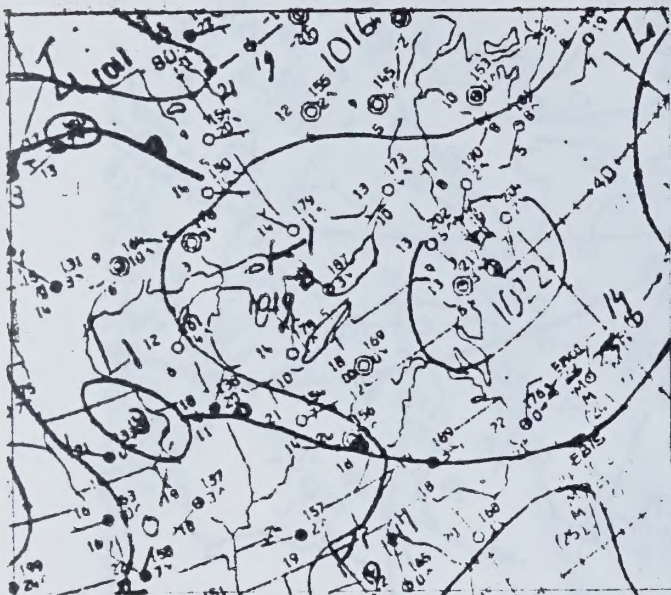


(a) 29 July 1977 1300 EST



(b) 30 July 1977 1300 EST

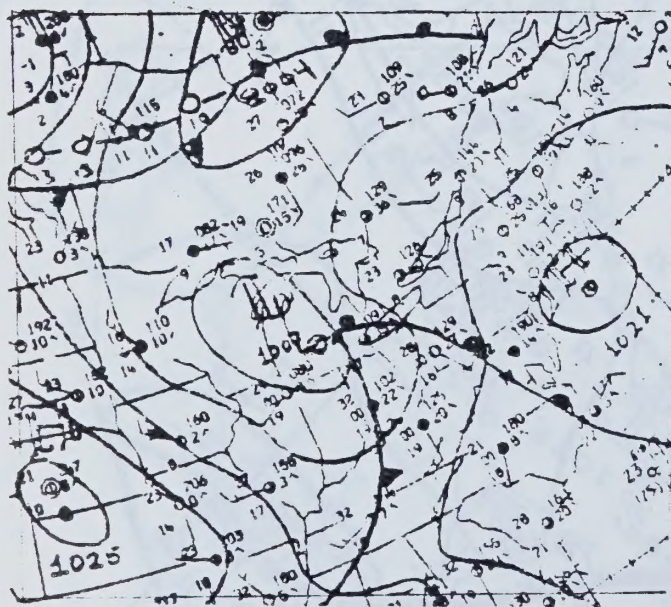
Fig. 68 Surface Synoptic Weather Conditions



(a) 0100 EST



(b) 0700 EST

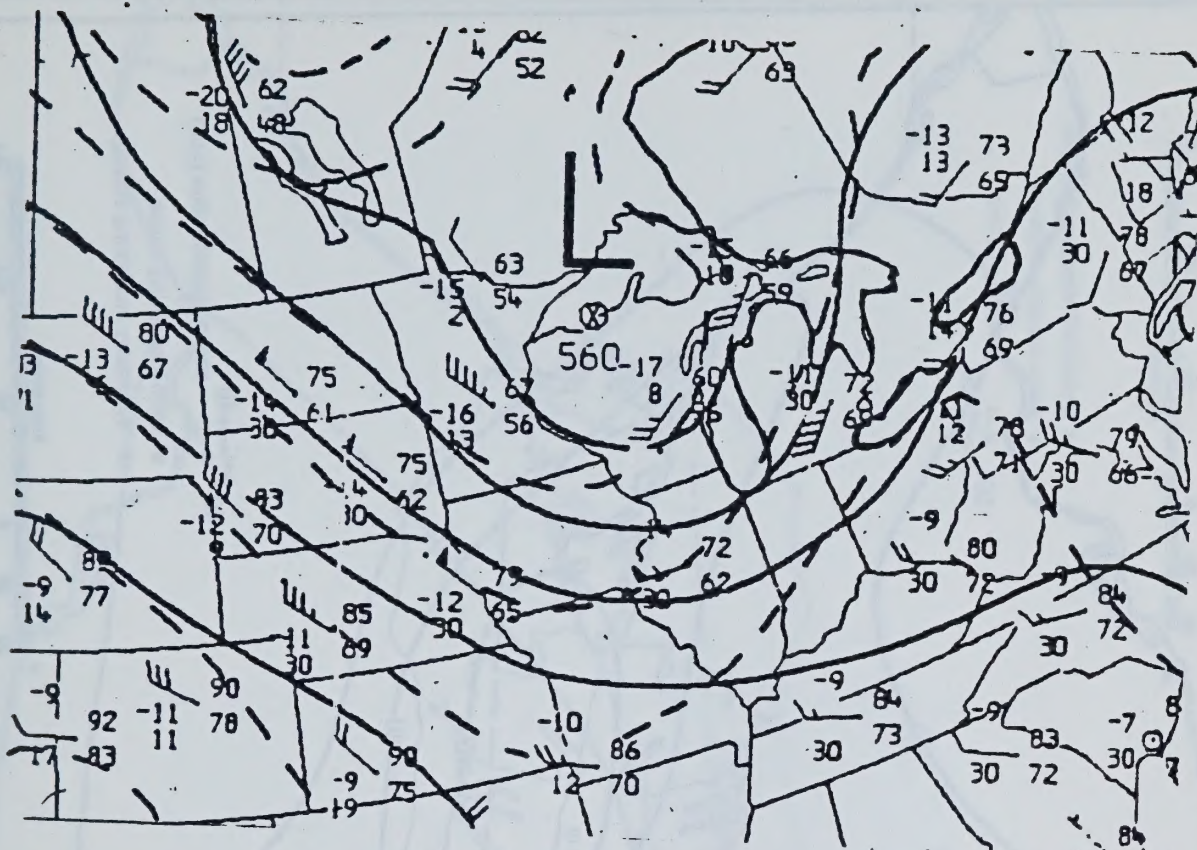


(c) 1300 EST

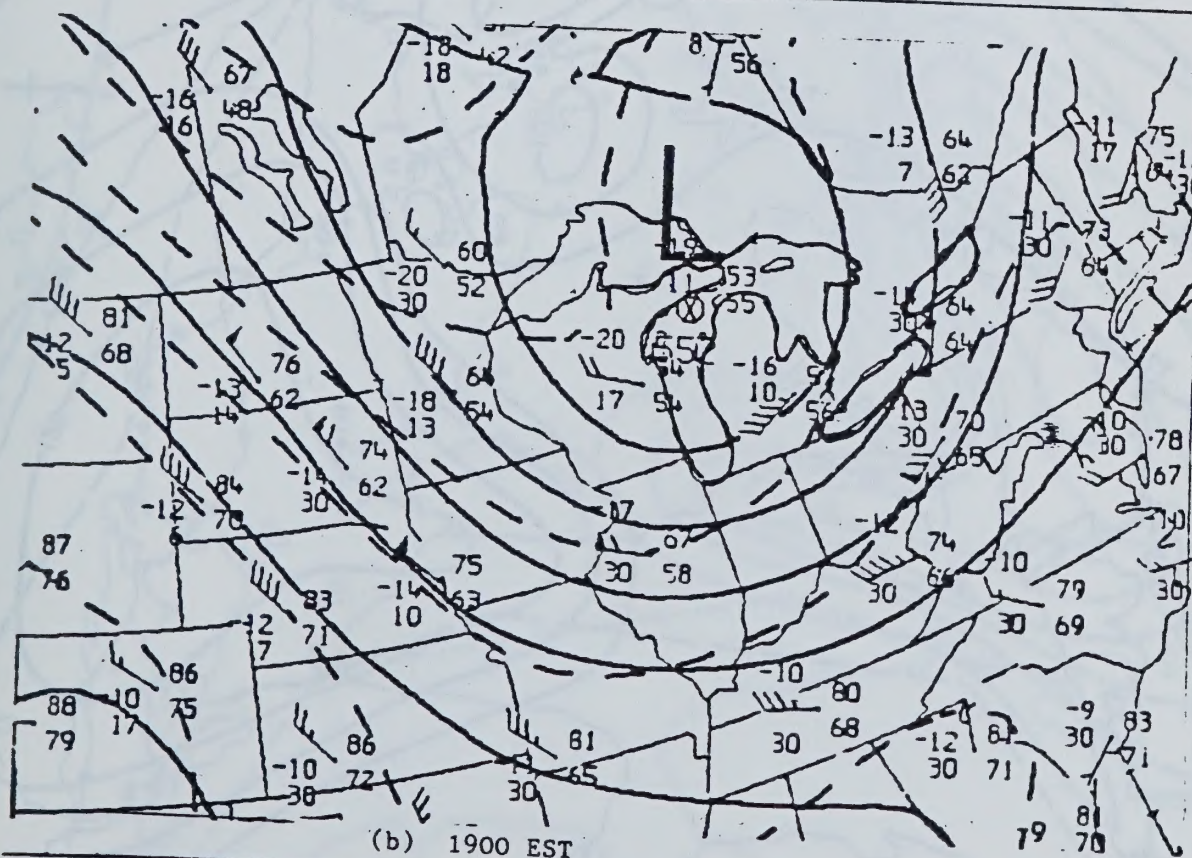


(d) 1900 EST

Fig.(69) Surface Synoptic Weather Conditions on July 31, 1977



(a) 0700 EST



(b) 1900 EST

Fig. (70) 500 MB. Synoptic Weather Conditions
on 31 May 1977

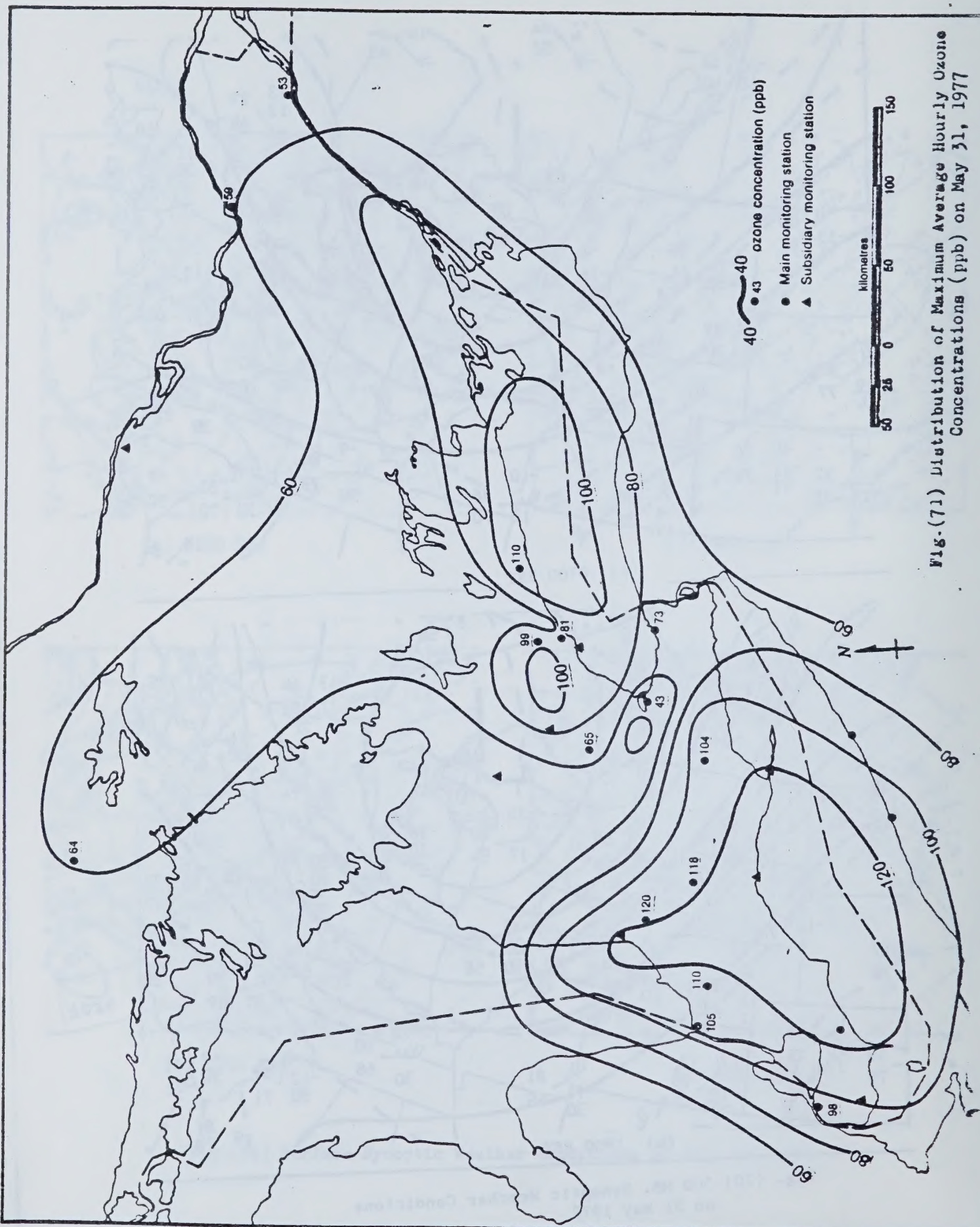


Fig. (71) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on May 31, 1977

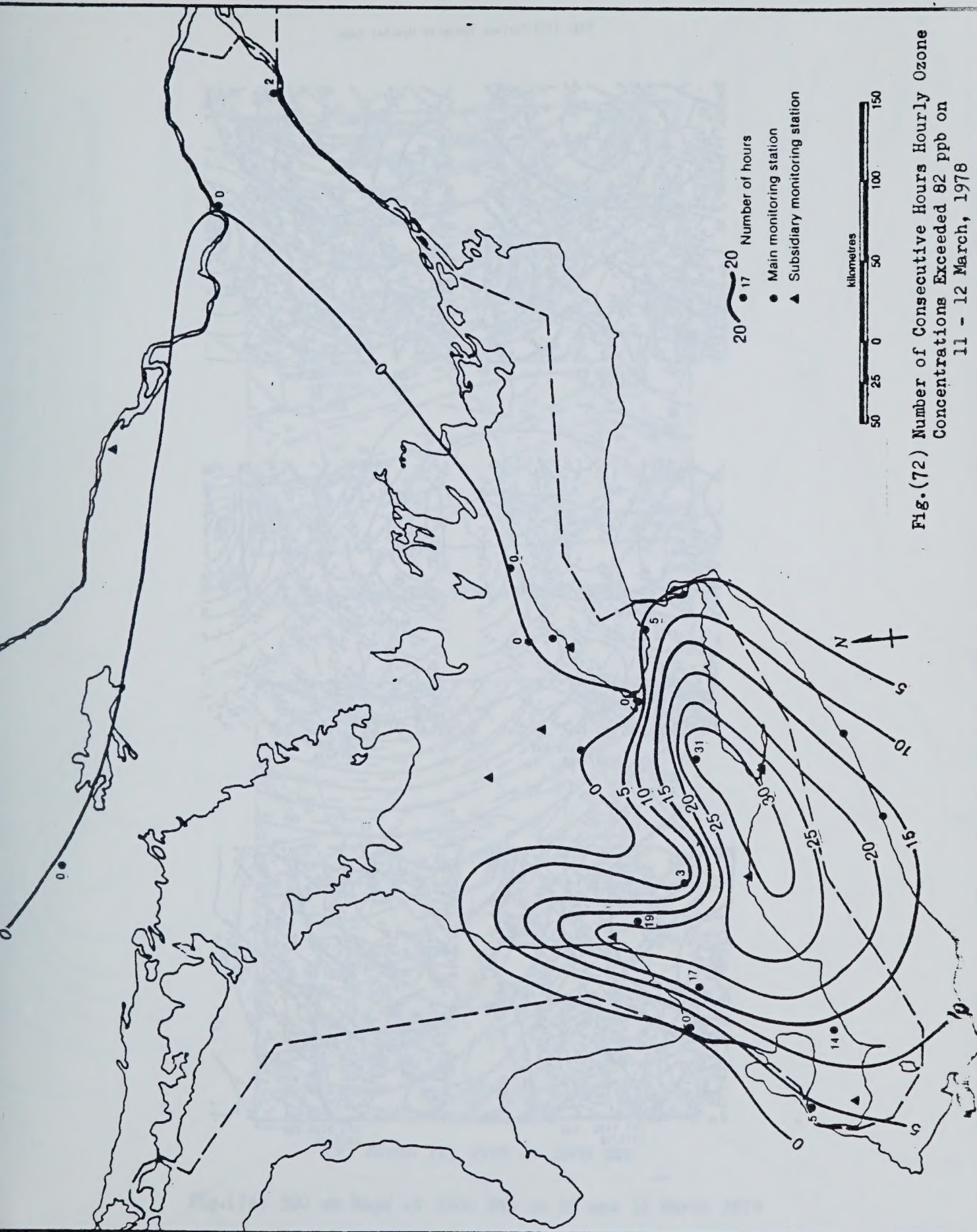


Fig.(72) Number of Consecutive Hours Hourly Ozone Concentrations Exceeded 82 ppb on 11 - 12 March, 1978

Fig. (73) Surface Synoptic Weather Maps



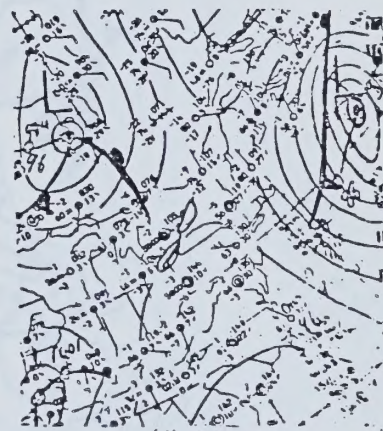
(a) 1300 EST
10/3/78



(b) 1900 EST
10/3/78



(c) 0100 EST
11/3/78



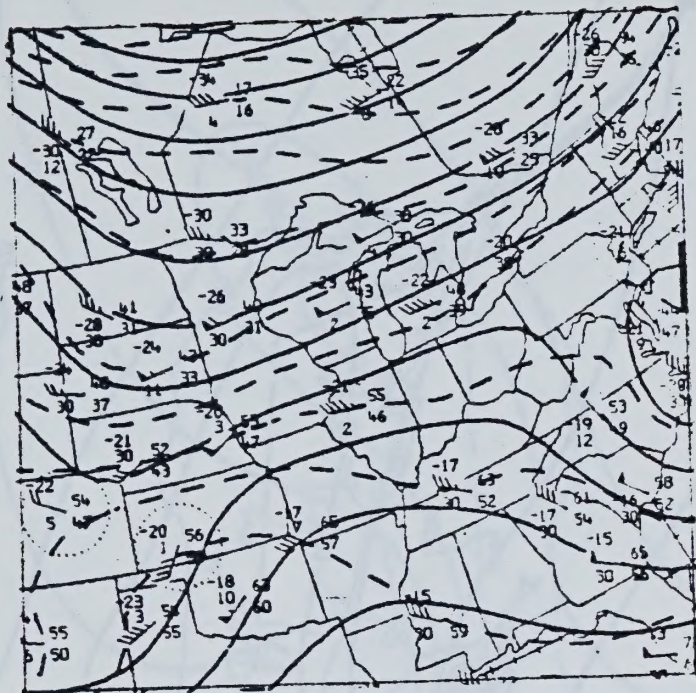
(d) 0700 EST
11/3/78



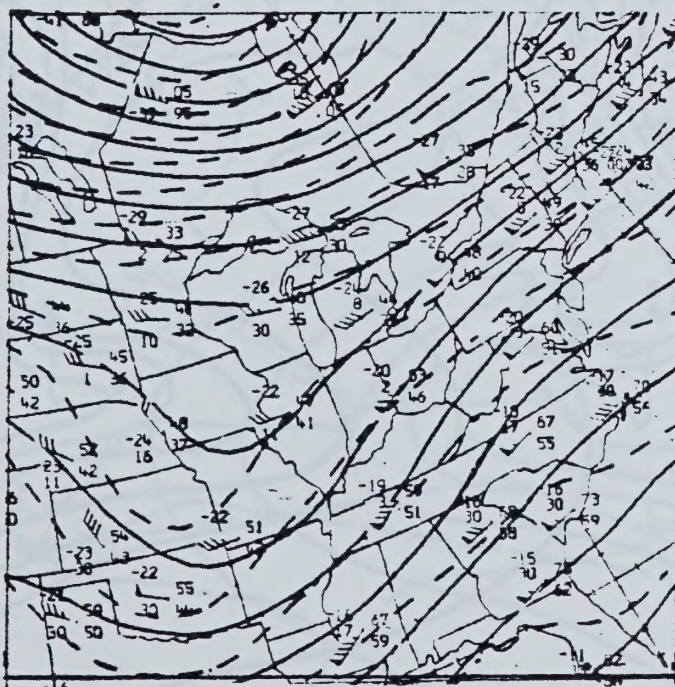
(e) 1900 EST
11/3/78



(f) 0700 EST
12/3/78



(a) March 10, 1978 at 1900 EST



(b) March 11, 1978 at 1900 EST

Fig.(74) 500 mb Maps at 1900 EST on 10 and 11 March 1978

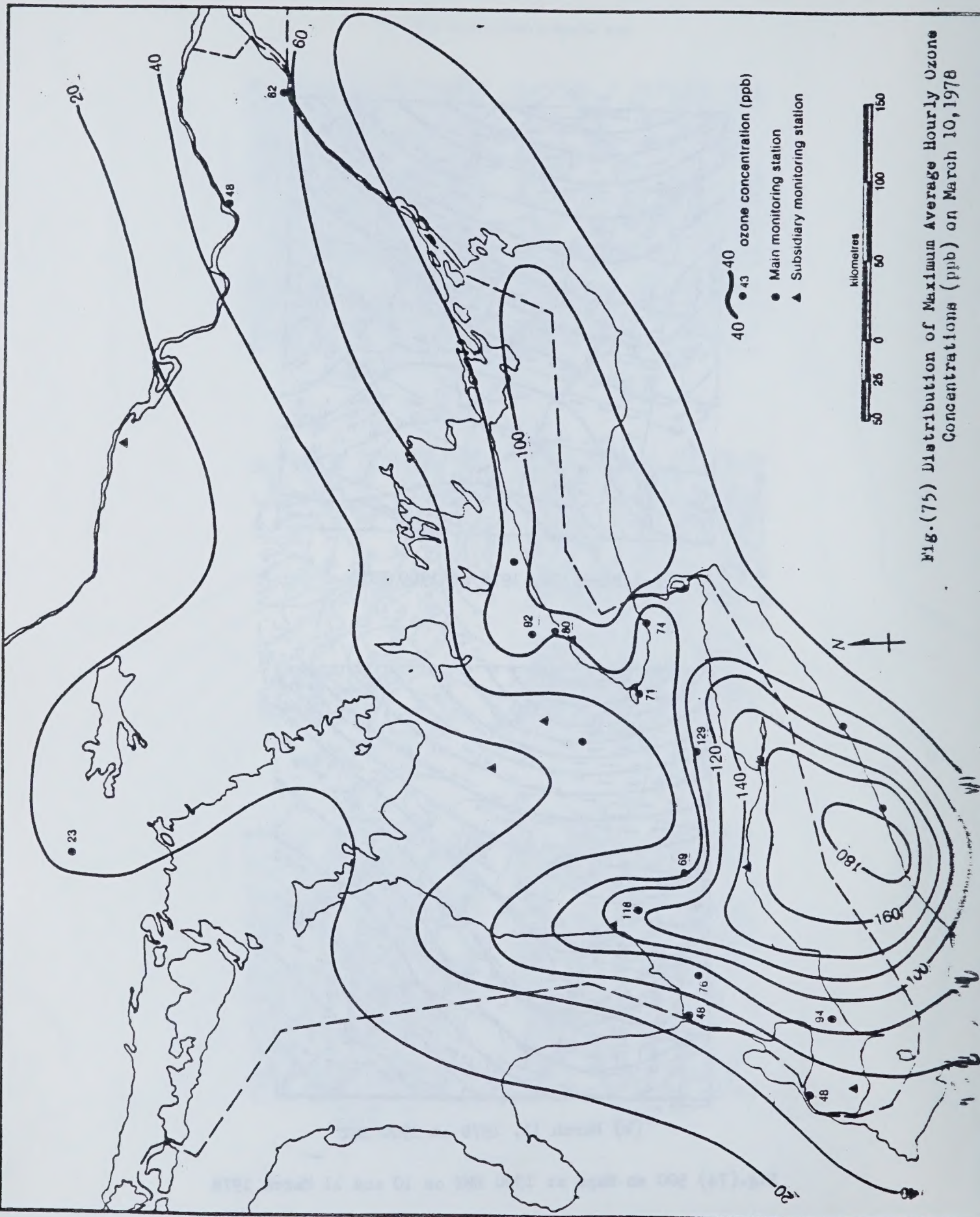
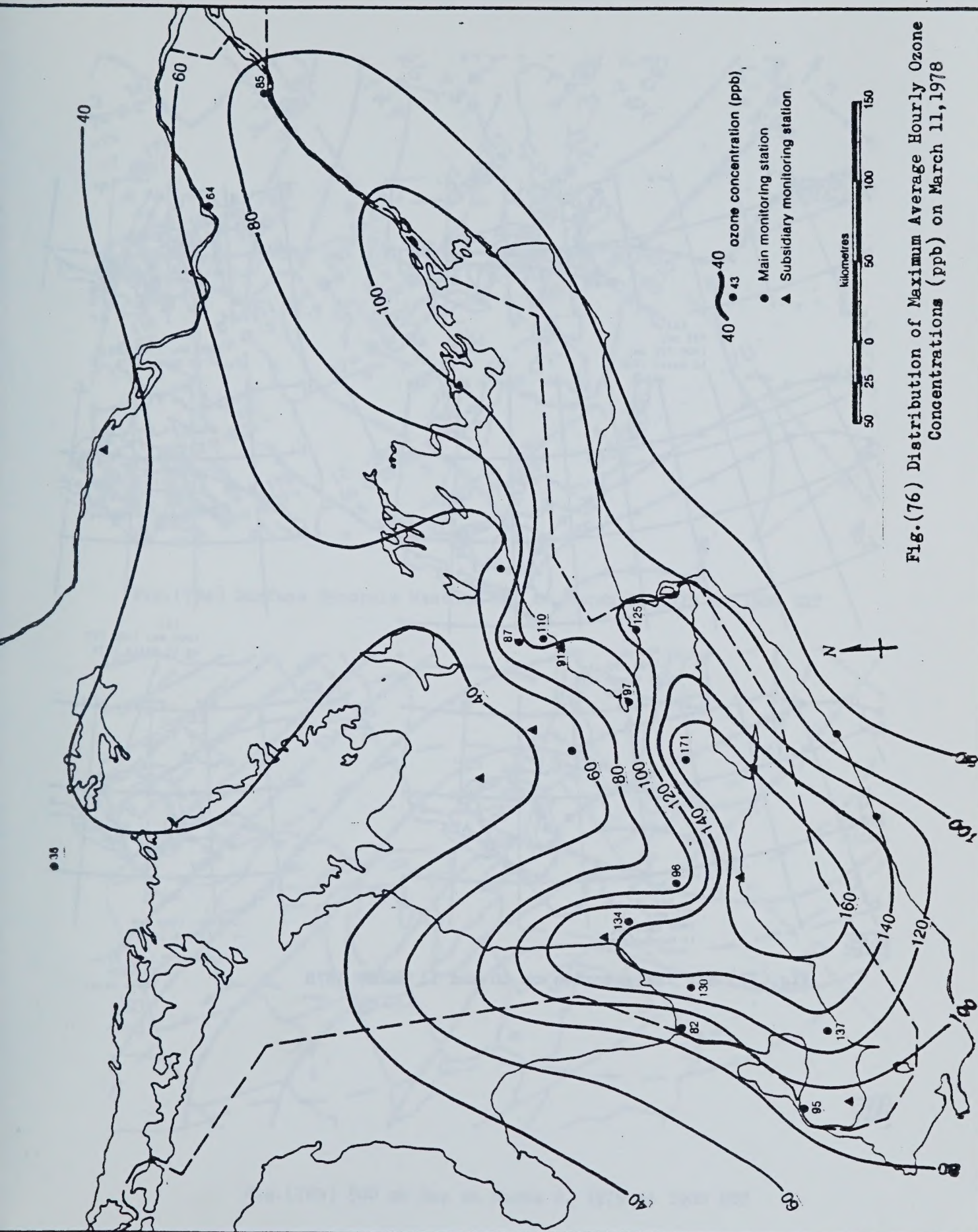
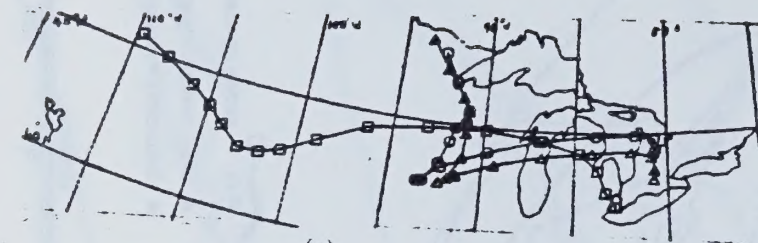
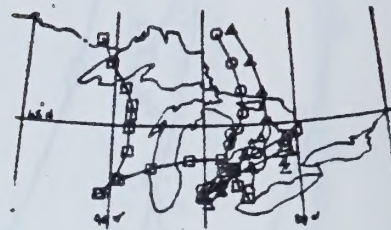


Fig.(75) Distribution of Maximum Average Hourly Ozone Concentrations (ppb) on March 10, 1978





(a)
925 mb.
1900 EST on.
10 March 1978



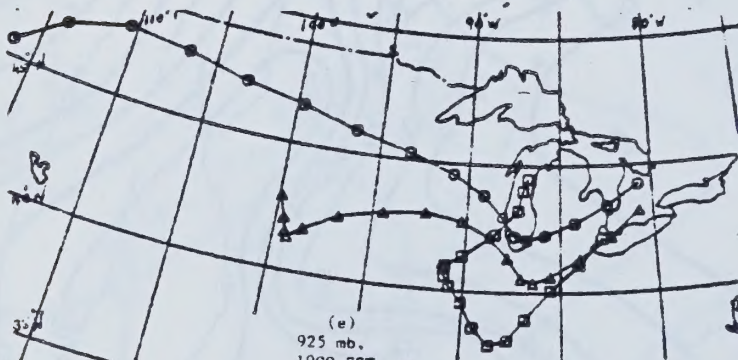
(b)
1000 mb, 1900 EST,
on 10 March 1978



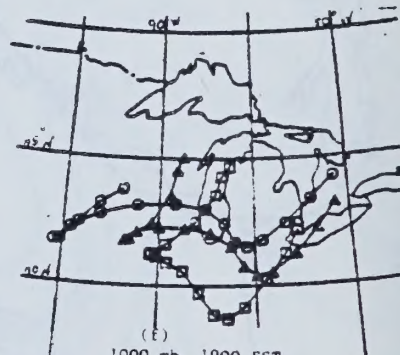
(c)
925 mb.
1300 EST, on
11 March 1978



(d)
1000 mb, 1300 EST
on 11 March 1978



(e)
925 mb.
1900 EST, on
11 March 1978



(f)
1000 mb, 1900 EST
on 11 March 1978

Legend: ○ Long Point
△ Toronto
□ Chalk River

Fig.(77) Air Trajectories on 10 and 11 March 1978

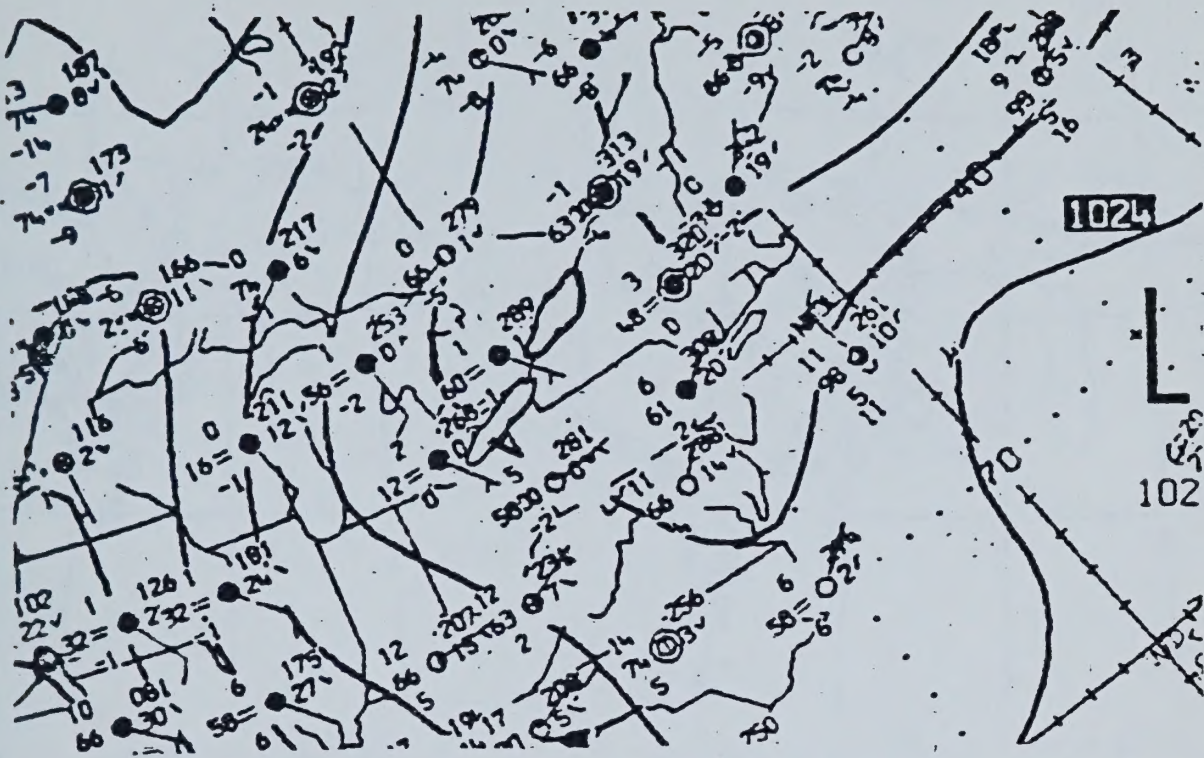


Fig.(78a) Surface Synoptic Weather Map on March 2, 1979 at 1900 EST

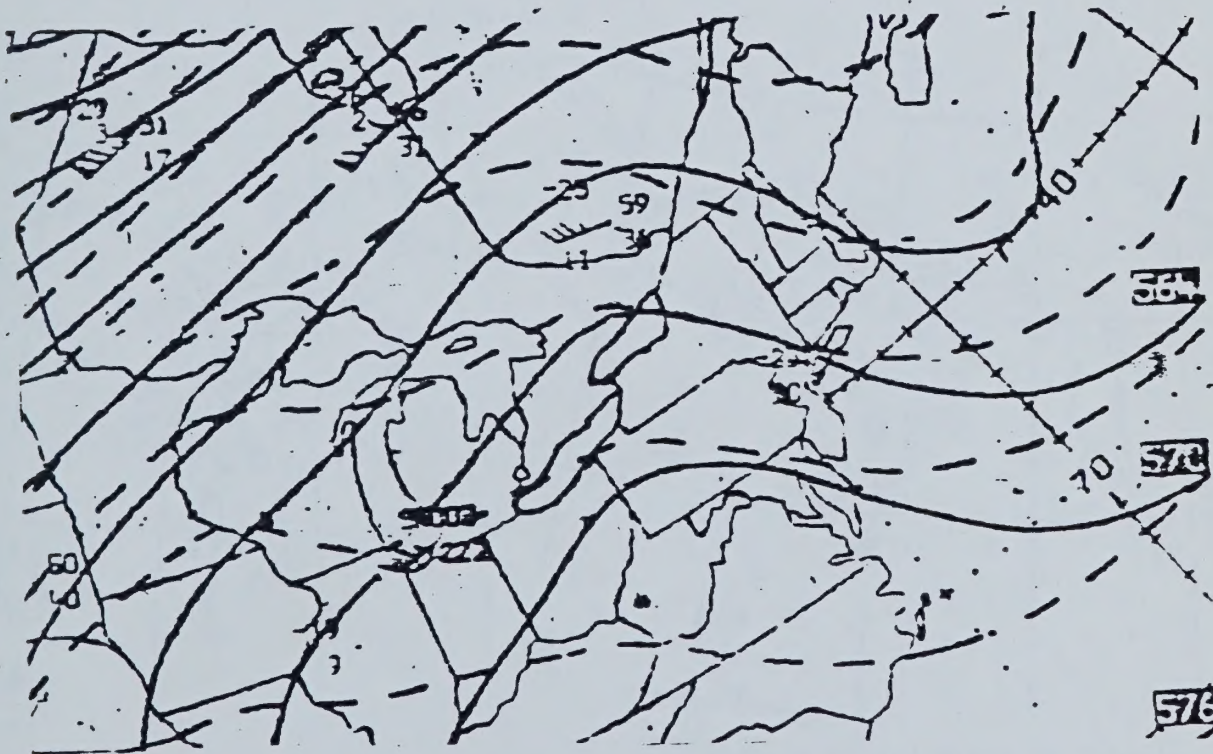


Fig.(78b) 500 mb Map on March 2, 1979 at 1900 EST



1000 mb trajectories at 1300 EST

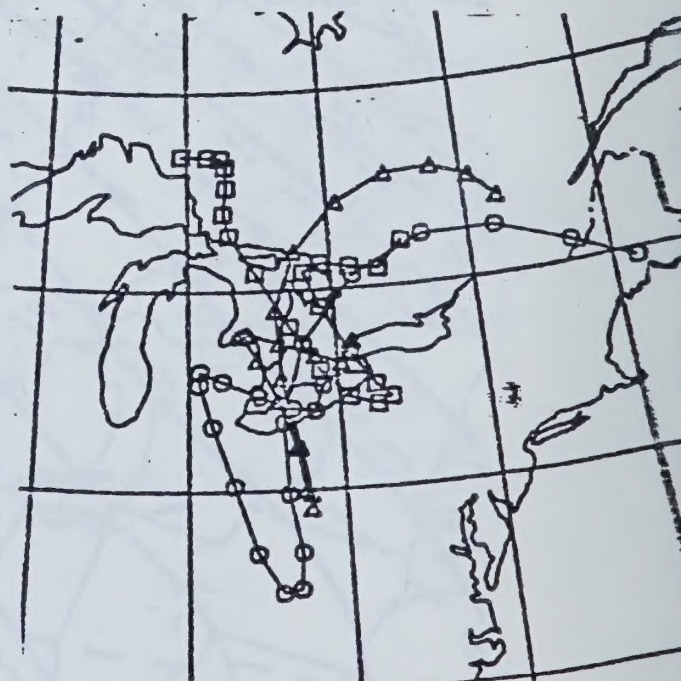


925 mb trajectories at 1300 EST

Legend: O Long Point
 Δ Toronto
 □ Chalk River



1000 mb trajectories at 1900 EST



925 mb trajectories at 1900 EST

Fig.(79) Air Trajectories on March 2, 1979

